AMERICAN UNIVERSITY OF BEIRUT

3D SIMULATION FOR BREAD BAKING IN AN INDUSTRIAL BAKING OVEN ACCOUNTING FOR PHYSICAL AND CHEMICAL PHENOMENA OCCURRING DURING BAKING

by
MOHAMAD HASSAN AL NASSER

A thesis
submitted in partial fulfillment of the requirements
for the degree of Master of Engineering
to the Department of Mechanical Engineering
of the Faculty of Engineering and Architecture
at the American University of Beirut

Beirut, Lebanon
April 2019

AMERICAN UNIVERSITY OF BEIRUT

3D SIMULATION OF A MATHEMATICAL MODEL ACCOUNTING FOR PHYSICAL AND CHEMICAL PHENOMENA FOR A BREAD DURING BAKING INTEGRATED IN AN INDUSTRIAL BAKING OVEN

by

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AKNOWLEDGMENTS

I would like express my sincere gratitude and special thanks for my advisor Prof. Fadl Moukalled for all his support and guidance through all my journey at AUB. Not just in teaching and guiding me in the right academic way, but also providing me with his advice and standing beside me all the time and in all issues.

I would also thank Prof. Marwan Darwish and Prof. Issam Lakkis for their academic support and advice and being members of my thesis committee.

Many thanks goes to my colleagues at the CFD lab Hiba Kobeissi, Mohamad Ali Fakih and Mohamad Mahdi Alloush for their all their help and support.

The most special thanks goes to my family and friends who were always beside me and motivated me through all my life.

Finally, I would like to acknowledge the financial support of the University Research Board of the American University of Beirut grant award.

AN ABSTRACT OF THE THESIS OF

Mohamad Hassan Al Nasser for Master of Engineering
Major: Mechanical Engineering

Title: 3D Simulation of a Mathematical Model Accounting for Physical and Chemical Phenomena for a Bread during Baking Integrated in an Industrial Baking Oven

The aim of this project is to predict numerically the baking of a bread. This is done through a detailed analysis of both the oven and the bread placed inside the oven during the baking process. The purpose is to achieve a better understanding of the complex phenomena occurring during baking in order to improve the design of the oven and to optimize the baking process.

The work is divided into two parts. The first part is directed towards understanding the transfer phenomena occuring during baking by simulating a full three-dimensional industrial baking oven. The oven is mainly divided into the following four parts: (1) heat exchanger, (2) blower, (3) baking chamber and racks, (4) and airflow. A dynamic mesh is used to simulate the motion of the blower.

The second part consists of analyzing the bread during the baking process. First a mathematical model of the baking process that accounts for chemical and physical changes in the bread will be developed and tested. This includes evaporation/ condensation, volume expansion, release of carbon dioxide (CO_2), and formation of pores, crumb and crust layers. In a second step, the mathematical bread baking model is integrated with the oven model to simulate the full process. This involves performing analysis, using a dynamic mesh, of the multiphase flow and heat transfer fields within the oven in addition to changes in bread properties and volume.

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CHAPTER I

INTRODUCTION

Bread is one of the earliest food adopted by humanity. Indeed, it is the first processed food by people down through history. According to the US Department of Agriculture, the different types of bread originate from wheat, which is the second most produced crop in the world.

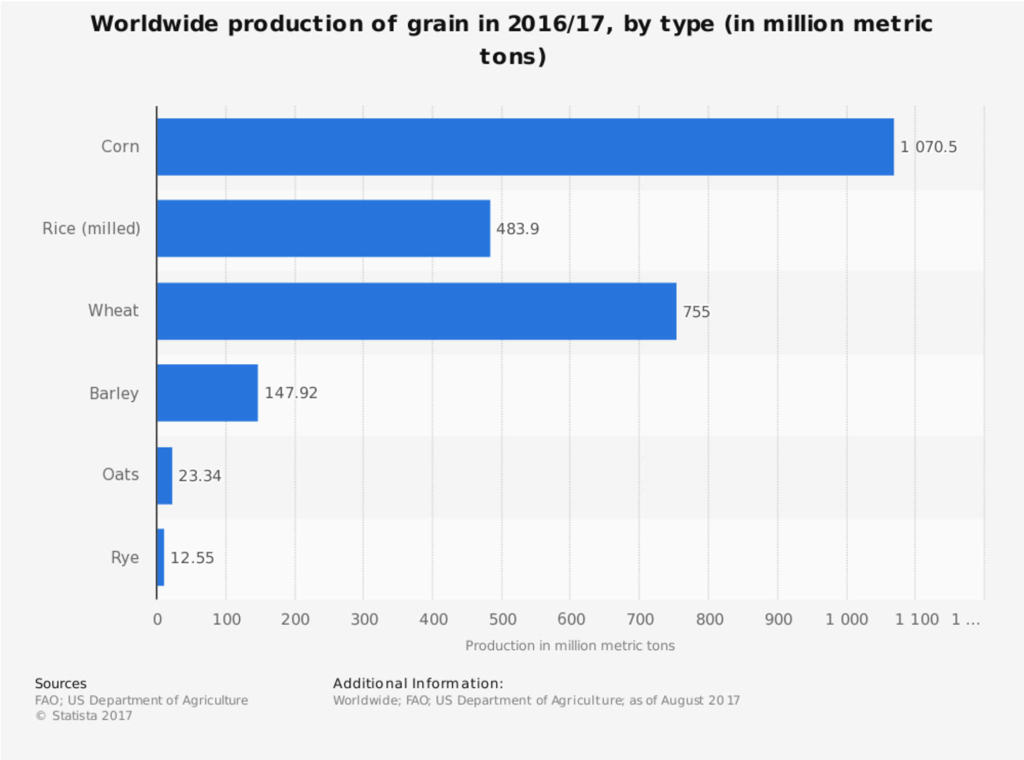

Figure 1: Grain production statistics by the US Department of Agriculture [1]

This fact makes the process of baking and bread production very spread-out and recognizable. The final product, which is a porous and light material, is affected significantly by the portions and content in the dough [2]. Moreover, bread quality is also affected by the baking process. Despite all reported studies, additional knowledge is still required to fully understand this process.

Computational Fluid Dynamic (CFD) is a numerical tool for predicting fluid flow, heat transfer, and other transfer phenomena. Even though the drive behind its development was the aeronautic and aerospace industries, it has grown to become an essential tool in a range of other industries [3]. CFD found its way to food processing in the past decade due to the increase in computational power and the existence of reliable software such as FLUENT, CFX, OpenFoam, etc. [4].

Bread production is considered to be a very complicated procedure that involves changes in the physical and chemical composition of the dough during baking. The most important changes include starch gelatinization, protein degradation, evaporation/condensation, CO_2 gas release, formation of crumb and crust and, most importantly, volume expansion due to formation of pores. Before dealing with the bread itself, one of the most important factors in baking is the design of the oven and its operating conditions. According to Chhanwal et al. [5], bread is mainly evaluated by its texture (crust percent), moisture content, color (browning), and structure. All the aforementioned characteristics are related directly to the performance of the oven and its operating conditions (temperature and water content). Thus, different setups lead to different qualities of the product.

The many existing types of ovens can be broadly classified as either continuous or discontinuous ovens. Continuous ovens are commonly used for baking and are of interest in this study. These ovens can be further sub-categorized, based on their heat transfer mode, as forced convection ovens, radiative infrared ovens, or combined ovens (i.e. involving a combination of both convection and radiation heat transfer modes). The aim of the different designs is to achieve the optimum operating conditions by controlling the heat transfer rate in order to produce the best product. Purlis [6] conducted a theoretical study to optimize the baking process. In his work, he combined forced convection with infrared radiation to obtain the best efficiency.

Electrical ovens have been thoroughly studied in the literature [7-9]. Those relying solely on radiation suffer the drawback of having limited baking space. This shortcoming arises because baking requires a direct exposure between the source of radiation and the bread. This drawback is not found in forced convection ovens permitting a larger number of breads to be baked at the same time. The most commonly used convection-based type is the continuous rotary rack oven. As reported in [5], energy optimization of convective ovens is critically dependent on the position of heat source and blower. Despite their wide use, the method of operation of convective ovens is usually determined experimentally [10], which renders optimization to be a difficult task and consequently leading to an excessive loss of energy. Therefore there is a need to conduct numerical simulations in order to improve their designs (by producing uniform heat distribution inside the oven) and optimize their performance.

Therdthai et al. [11] identified the major variables affecting the baking process to be the baking time, baking temperature, moisture content inside the oven, and distribution of heat flux in the oven. Although all these parameters are interdependent, temperature is the most important factor [12]. According to Wong et al. [13] the bread baking process is divided into 4 stages. The first phase occurs during the first quarter of the baking time. During that period, the bread is entered into the hot oven and once its temperature reaches 333 K, the enzymatic reactions are inactivated and the yeast is killed. Moisture evaporation, starch gelatinization, and protein degradation take place during the second and third stages of the baking process and require almost half the baking time (i.e. the second and third quarters of the baking time).The fourth stage represents the final quarter of the required baking period and is accompanied by volatilization of organic compounds, formation of crust, and browning of the dough surface. The formation of crust is usually coupled to the loss of moisture which occurs at the bread surface. Internal evaporation/condensation occurs in the flowing sequence:

- water evaporates from the wormer side of the gas cell absorbing latent heat
- water vapor is transported to the colder side of the cell by concentration gradient
- water condenses along the colder side of the cell wall
- heat and mass are also transferred by diffusion

The whole mechanism is repeated until the temperature of the bread reaches 100 °C. Beyond that temperature no condensation occurs [5]. Any excess in baking time or temperature leads to extra crust formation, darker color of surface, low moisture content, and shrinkage of bread size [14].

Several investigators have proposed mathematical models to describe the bread baking process. Zanoni et al. [15] developed a finite element based numerical model to study the details of the process. The model proposed the formation of an evaporation front on the surface of the bread that propagates into the bread and leads to the formation of two layers denoted by crust and crumb. Zhang et al. [16] proposed a mathematical model for bread baking that fully couples the transport and deformation equations. Pulris et al. [17, 18] suggested a general relation between evaporation/condensation and the moving boundary of the bread that can be implemented for any baking process.

This study aims at building a full three-dimensional multiphase model of an industrial baking oven. A detailed simulation is performed to analyze the flow and temperature distribution inside the oven. A mathematical model of the bread is proposed and integrated with the oven to predict the moisture content and physiochemical changes during the baking process. The results are expected to foster our understanding of the various phenomena occurring during bread baking.

CHAPTER II

METHODOLOGY

A. Part 1: Physical model

The oven model consists of the following two main compartments: (i) the clean air compartment, and (ii) the combustion gases compartment. Communication between the two sections occurs by heat transfer only through a heat exchanger. No transfer of mass or mixing between the clean and dirty gases takes place. The industrial bread baking oven configuration considered in this study is schematically depicted in Figure 2.

The clean air section includes the blower, air-side heat exchanger, baking chamber, and inlet and return airflows. The blower drives the air with a speed of 6 $\mathrm{m/s}$. The air passes over the heat exchanger and exchanges heat with the flue gases flowing inside. Then, air enters the baking chamber after being heated. In the baking chamber, heat is transferred by convection to the bread by the hot air causing the bread to bake. During baking, water vapor and $\mathrm{CO_2}$ are released to the hot clean air. This process is continuous and is stopped once the bread is cooked and has become ready to eat.

In the combustion gases compartment, which is shown in Figure 3, flue gases enter the heat exchanger with a temperature of 1073 K at a rate of 0.002 kg/s. While moving inside the heat exchanger, combustion gases lose heat to the air flowing on the outer side of the heat exchanger and exit with a temperature of 470 K.

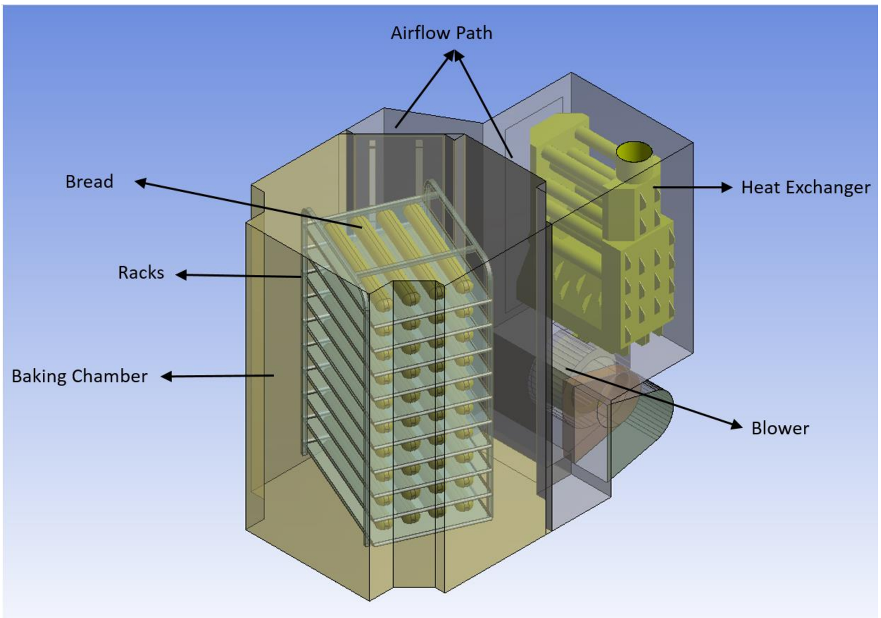

Figure 2: Schematic showing the oven assembly

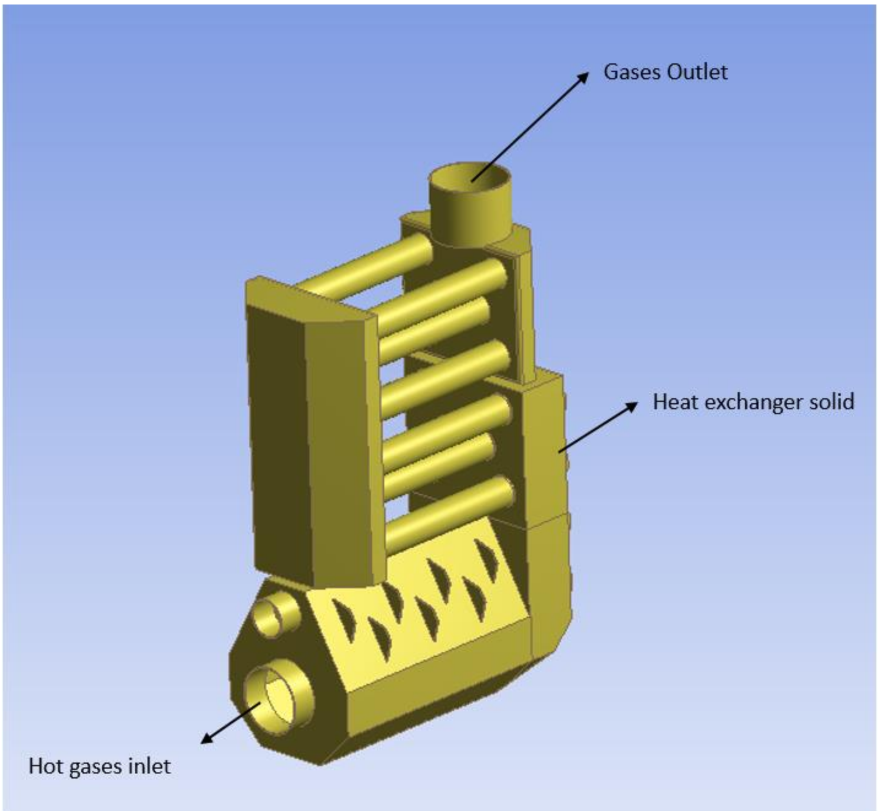

Figure 3: Schematic showing the flow path of the combustion gases.

1. Conservation equations

The flow in the clean air compartment is initially composed of dry air and water vapor. However, as baking proceeds, additional water vapor and some carbon dioxide are released from the bread to the air. Further, the loaf itself contains liquid water that undergoes and evaporation/condensation process. Therefore, the clean side compartment contains two fluids that are respectively in the gas and liquid phases. The gas phase is multispecies composed of dry air, water vapor, and carbon dioxide. The liquid phase is composed simply of liquid water. The mixture multiphase model is adopted to simulate the flow in this compartment. Besides solving the continuity, momentum, energy, turbulence model, and liquid volume fraction equations, additional conservation relations tracking the mass fractions of water vapor and carbon dioxide in the gas phase are also needed. Moreover, in the flue gases compartment, the flow is treated as a single multispecies gas phase (SOOT, CO_2, NO_x ... etc).

Simulations will be conducted using a commercial CFD tool (**ANSYS FLUENT®**). The equations mentioned below, which are needed to solve the problem, are described next [19]. The multiphase form of the equations is presented, from which the single phase can easily be deduced.

a. Continuity equation:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot \left(\rho_m \mathbf{u}_m \right) = 0 \qquad (1)$$

$$\mathbf{u}_m = \frac{\sum_k \alpha_k \mathbf{u}_k}{\rho_m} \qquad \rho_m = \sum_k \alpha_k \rho_k \qquad (2,3)$$

where

- ρ Density
- α Volume fraction
- $\mathbf{u}$ The velocity vector
- m refers to mixture
- k refers to phase

b. Momentum:

$$\frac{\partial(\rho_m \mathbf{u}_m)}{\partial t} + \nabla\cdot(\rho_m \mathbf{u}_m \mathbf{u}_m) = -\nabla p + \nabla\cdot\left(\overline{\overline{\tau}}_{ij}\right) + \rho\mathbf{g} + \mathbf{F} + \mathbf{u}_{dr,k}\sum_k \alpha_k \rho_k \mathbf{u}_{dr,k} \tag{4}$$

(5)

$$\begin{aligned} \overline{\overline{\tau}}_{ij} &= \mu_{m,eff}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu_{m,eff}\frac{\partial u_k}{\partial x_k}\delta_{ij} \\ \mu_{m,eff} &= \sum_k \alpha_k\left(\mu_k + \mu_{k,t}\right) \quad for \;\; i,j = 1,2,3 \end{aligned} \tag{5,6}$$

where

- $\boldsymbol{F}$ external body force
- $\boldsymbol{g}$ gravitational force
- $\mathbf{u}_{dr,k} = \mathbf{u}_\mathrm{k} - \mathbf{u}_\mathrm{m}$ drift velocity

c. Energy equation:

$$\frac{\partial}{\partial t}\left(\sum_k \alpha_k \rho_k E_k\right) + \nabla\cdot\left[\sum_k \alpha_k \mathbf{u}_k\left(\rho_k E_k + p\right)\right] = \nabla\cdot\left(k_{eff}\nabla T\right) + S_h \tag{7}$$

where

- S_h source term
- k_{eff} effective thermal conductivity
- E_k total energy of phase k

$$E_k = \left(\sum_j Y_j h_j \right)_k + \frac{p}{\rho}, \qquad h_j = \int_{T_{ref}}^{T} c_{p,j} dT \tag{8}$$

d. <u>Species (Y_v, Y_c):</u>

Water vapor:

$$\frac{\partial(\rho Y_v)}{\partial t} + \nabla \cdot (\rho \mathbf{u} Y_v) = -\nabla \cdot (\mathbf{J}_v) + S_v \tag{9}$$

$$\mathbf{J}_v = -\left(\rho D_{v,m} + \frac{\mu_t}{Sc_t} \right) \nabla Y_v \tag{10}$$

Carbon dioxide:

$$\frac{\partial(\rho Y_c)}{\partial t} + \nabla \cdot (\rho \mathbf{u} Y_c) = -\nabla \cdot (\mathbf{J}_c) + S_c \tag{11}$$

$$\mathbf{J}_c = -\left(\rho D_{c,m} + \frac{\mu_t}{Sc_t} \right) \nabla Y_c \tag{12}$$

Where

- v *water vapor*
- c *carbon dioxide*
- Y mass fraction
- J diffusion flux
- $Sc_t = \frac{\mu_t}{\rho D_t}$ turbulent Schmidt number

- μ_t , D_t turbulent viscosity and turbulent
- $D_{,m}$ mass diffusion coefficient

e. <u>Volume fraction:</u>

$$\frac{\partial\left(\alpha_l \rho_l\right)}{\partial t}+\nabla\cdot\left(\alpha_l \rho_l \mathbf{u}_m\right)=-\nabla\cdot\left(\alpha_l \rho_l \mathbf{u}_{dr,l}\right)+S_\alpha \tag{13}$$

where

- S_α rate of condensation

f. <u>Turbulence model [20]:</u>

$$\frac{\partial \rho k}{\partial t}+\nabla\cdot\left(\rho \mathbf{u} k\right)=\nabla\cdot\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\nabla k\right]+G_k+G_b-\rho\varepsilon+S_k \tag{14}$$

$$\frac{\partial \rho \varepsilon}{\partial t}+\nabla\cdot\left(\rho \mathbf{u} \varepsilon\right)=\nabla\cdot\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla k\right]+\rho C_1 S\varepsilon-\rho C_2 \frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}+C_{3\varepsilon}G_b+S_\varepsilon \tag{15}$$

With the model coefficients given by:

$$C_1=\max\left[0.43,\frac{\eta}{\eta+5}\right],\quad \eta=S\frac{k}{\varepsilon},\quad S=\sqrt{2S_{ij}S_{ij}},\quad \mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \tag{16}$$

$$
\begin{cases}
C_\mu = \dfrac{1}{A_0 + A_S \dfrac{kU^*}{\varepsilon}}, \qquad A_0 = 4.04, \quad A_S = \sqrt{6}\cos\varphi \\
U^* = \sqrt{S_{ij}S_{ij} + \tilde{\Omega}_{ij}\tilde{\Omega}_{ij}}, \quad \tilde{\Omega}_{ij} = \Omega_{ij} - 2\varepsilon_{ijk}\omega_k, \;\; \Omega_{ij} = \bar{\Omega}_{ij} - \varepsilon_{ijk}\omega_k \\
A_0 = 4.04, \quad A_S = \sqrt{6}\cos\varphi, \quad \varphi = \dfrac{1}{3}\cos^{-1}\left(\sqrt{6}W\right), \;\; W = \dfrac{S_{ij}S_{jk}S_{ki}}{\tilde{S}^3}, \;\; \tilde{S} = \sqrt{S_{ij}S_{ij}} \\
S_{ij} = \dfrac{1}{2}\left(\dfrac{\partial u_j}{\partial x_i} + \dfrac{\partial u_i}{\partial x_j}\right), \quad G_b = \beta g_i \dfrac{\mu_t}{\Pr_t}\dfrac{\partial T}{\partial x_i}, \quad \beta = -\dfrac{1}{\rho}\left(\dfrac{\partial \rho}{\partial T}\right)_p
\end{cases} \tag{17}
$$

In these equations, G_k represents the generation of turbulence kinetic energy due to the mean velocity gradients, G_b the generation of turbulence kinetic energy due to buoyancy, C_1, C_2, $C_{1\epsilon}$, and $C_{3\epsilon}$ constants, σ_k and σ_ϵ the turbulent Prandtl numbers for k and ϵ, respectively, S_k and S_ϵ user-defined source terms, and $\widetilde{\Omega}_{ij}$ the mean rate-of-rotation tensor viewed in a rotating reference frame with the angular velocity ω_k.

2. *Empty Oven Model*

Initially, an empty oven with no bread inside is simulated. Therefore a single phase flow with air volume fraction of 1 is used. As reported by the manufacturer, the blower rotates at a speed of 1400 rpm, which is equivalent to 146.5 rad/sec; this is considered to be a critical speed. The rotating flow within the blower region is simulated in a direct manner by setting the blades to rotate at the specified angular velocity. This setup gives exact performance of the blower without any approximation. In order to avoid the overlapping of element faces and the creation of negative volume elements during mesh motion, the time step was set at 10^{-4} seconds.

a. Thermo-physical properties, Initialconditions and Boundary conditions:

The composition and thermo-physical properties of the flue gases, and the thermal properties of the heat exchanger and the bread are obtained from the manufacturer and displayed in Tables 1-4. This is in addition to data related to the operation of the oven that are displayed in Table 5.

Table 1: Composition of the flue gas.

Element	Percentage Composition
Oxygen (O2)	6
Carbon Dioxide (CO2)	7
Water (H2O)	5
Nitrogen (N2)	78
Nitride Oxide (NOx)	1
Sulfur Oxide (SOx)	2
SOOT	1

Table 2: The thermo-physical properties of materials

property	**flue gas**	**oven-heat exchanger**	**bread**

Density (Kg/m3)	0.3379896	7750	705.4
Cp (J/Kg-K)	1190	500	1750
Thermal Conductivity (W/m-K)	0.0467226	16	0.309
Viscosity(Kg/m-s)	0.0000427	-	-

Table 3: Initial conditions provided by the manufacturer

Element	Percentage Composition
Mass flow rate of flue gas	0.0020 kg/s
Inlet Temperature of flue gas	1073 °C
Outlet Temperature of flue gas	743 °C
Blower Speed	**1400 rpm**
Blower air velocity	16.8 m/s
Racks' rotation speed	5 rpm

At the inlet to the flue gas compartment the mass flow rate and temperature are assigned. At the outlet, a pressure boundary condition is applied. For simplicity, walls are assumed to be adiabatic. The provided properties of the bread correspond to a bun of French baguette.

b. Simulation of the Empty Oven model:

In the first phase of the study, each part of the oven displayed in Figure 4 is meshed individually, then the full mesh (Figure 5) is generated using **Tgrid®**. The total mesh is composed of around **14 million** elements.

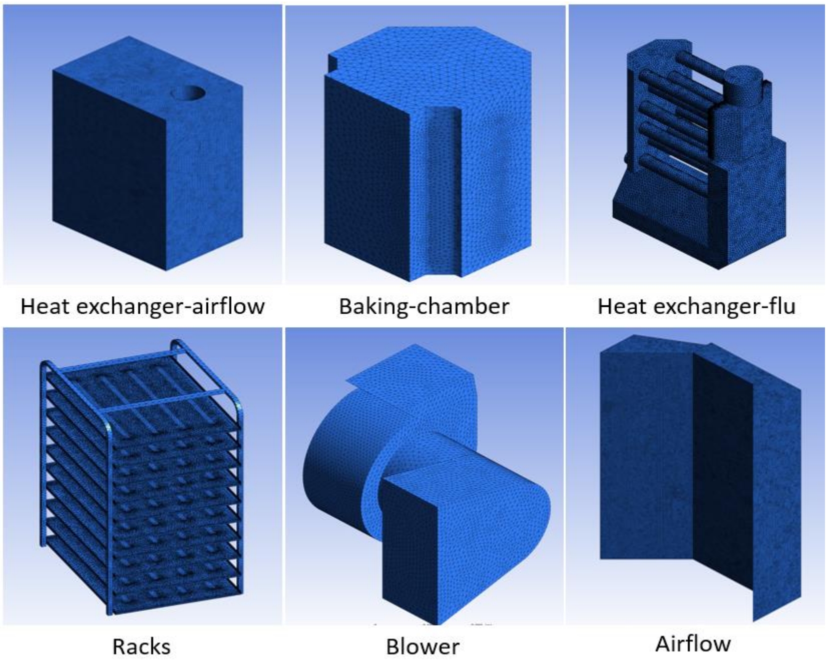

Figure 4: Figure showing the different elements of the meshed oven.

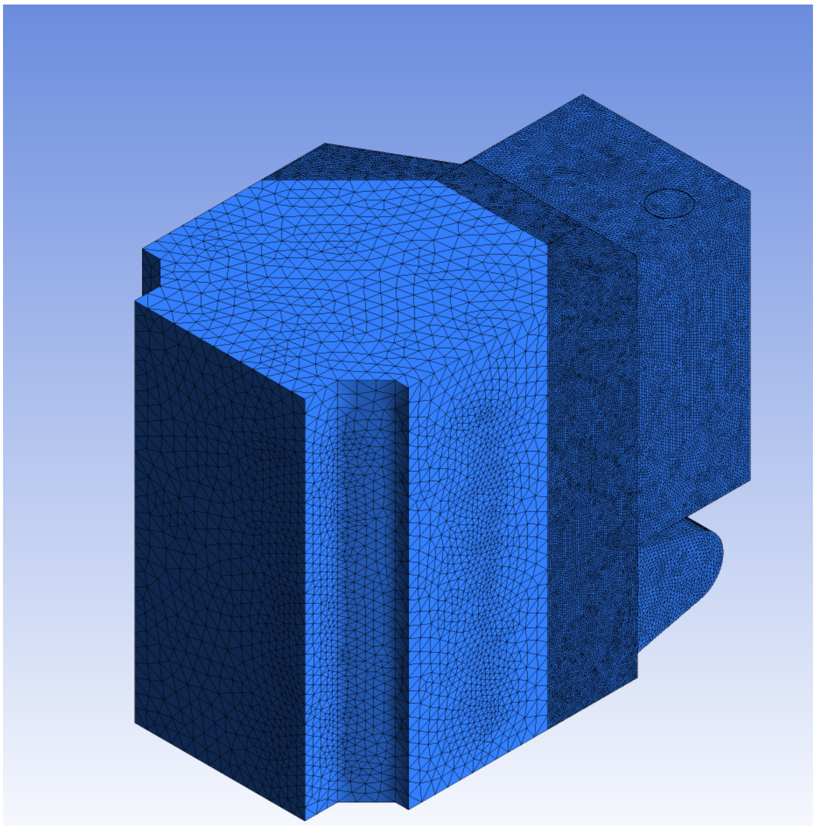

Figure 5: Meshed Oven

Preliminary steady and transient simulations were conducted to predict the flow and temperature fields in the empty oven. Results showing the velocity vectors of the air in the blower are displayed in Figure 6. The average air velocity at the outlet of the blower predicted numerically (15 m/s) is in good agreement with the measured value (16.8m/s).

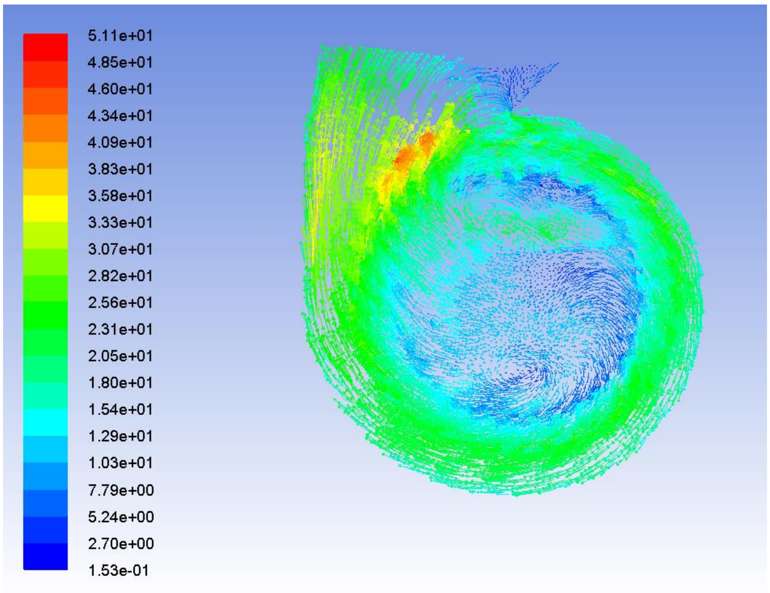

Figure 6: Velocity vectors of the air in the Blower

The predicted values of the flow fields in the heat exchanger at the flue gases side exactly match the experimental data. Where the velocity is 0.7 m/sec. (Figure 7)

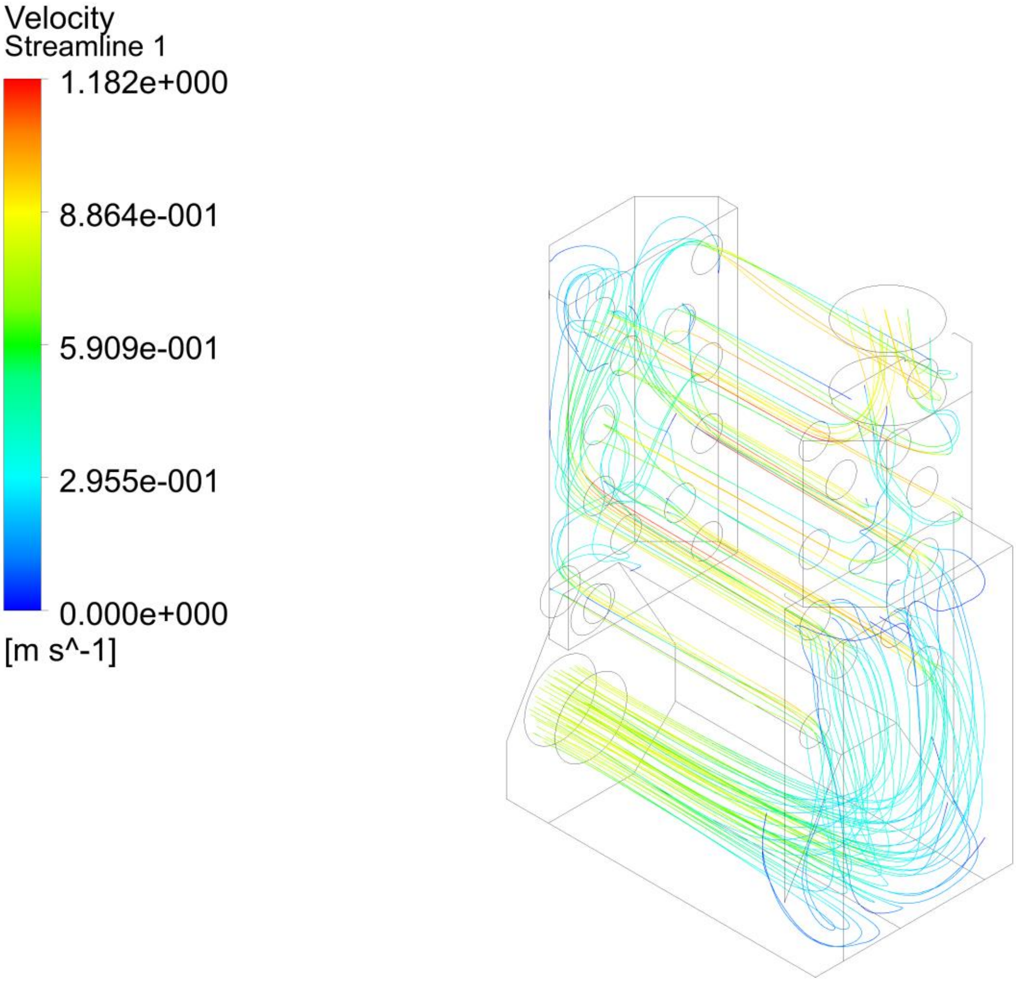

Figure 7: Velocity Streamlines of flow inside Heat exchanger gases part.

The oven is initially heated to 463 K before starting the baking process. Afterwards, the bread which is at room temperature 300 K is introduced into the baking chamber. Once the bread is introduced to the chamber the average temperature drastically drops in the first few seconds to reach 445 K then as the hot driven air enters the chamber the temperature increases to reach 490 K after 1 min and continues to increase slowly as time progresses. (Figure: 7)

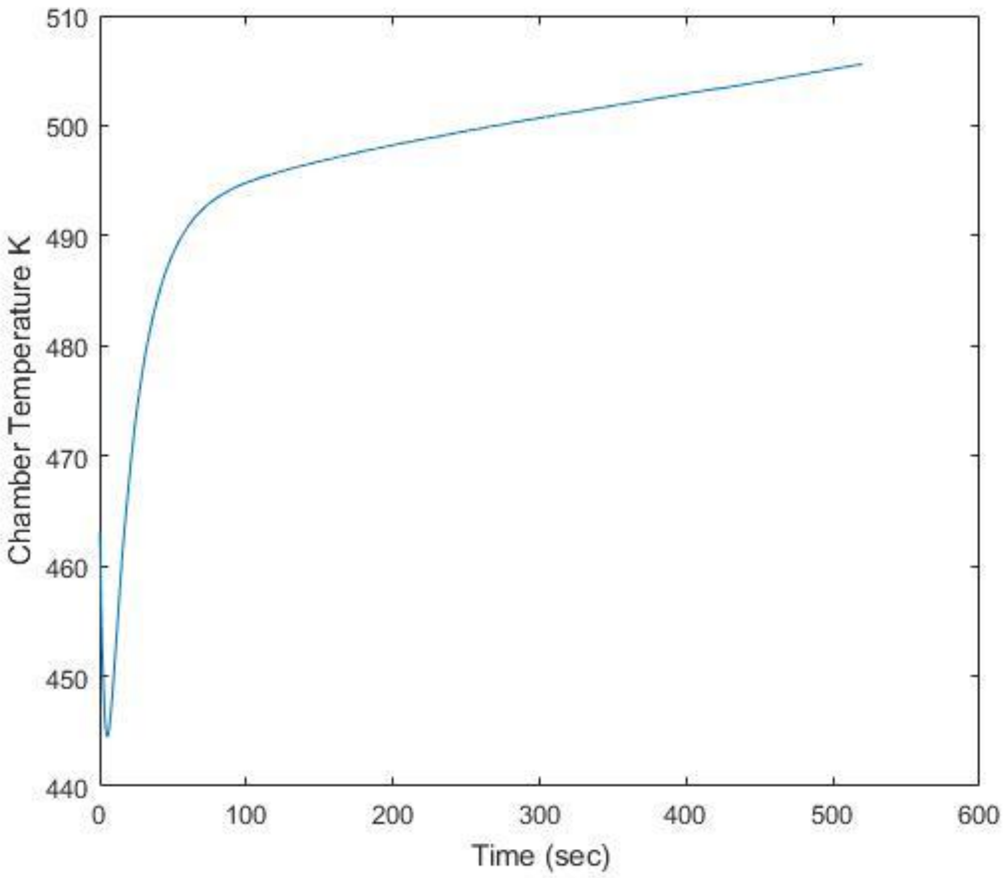

Figure 8 : Chamber Temperature Variation

On the other hand, upon placing the bread inside the chamber, its temperature starts to increase gradually and steadily at an average rate of & degrees per minute to reach the fully baked temperature of 373 K after 8.5 minutes, (Figure 8).

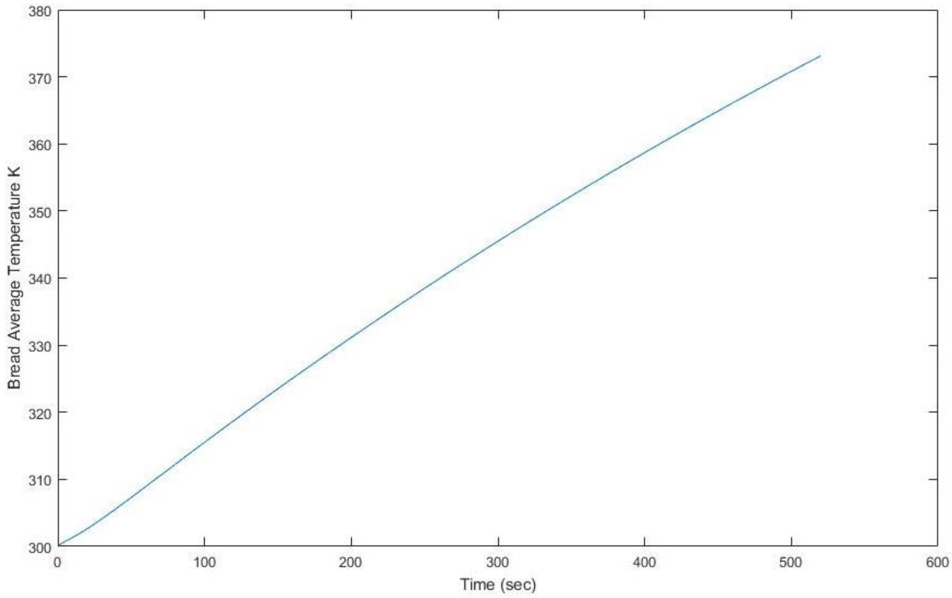

Figure 9: Plot showing the variation of bread temperature with time.

B. Part 2: Bread baking process

The second part of the work involves incorporating bread baking into the simulation, thereby accounting for the physical and chemical changes occurring in the dough during the process. Due to its complexity, the analysis of bread baking was based mainly on observation for a very long time (i.e., trial and error). Recently, some mathematical models were developed [2, 9, 15-17, 21-24]. These models could lead to a better quantification of the involved phenomena, assist in optimizing the process, and help improving the quality of the final product. The most important phenomena affecting bread baking are discussed next.

1. Starch gelatinization and protein degradation

Starch gelatinization, together with protein coagulation and the formation of brown crust are the critical factors determining the quality of the bread. Starch gelatinization and protein degradation contributes to several roles in bread baking. They are responsible for the formation of amorphous structure in the bread. Starch undergoes an irreversible reaction where the intermolecular bonds breaks down and absorbs water (swelling), followed by melting of crystalline component. Gelatinization of starch occurs mainly between 338 K and 353 K. This causes most of water to be absorbed before evaporation condensation occurs. This fact limits the mobility of water which can be neglected inside the bread in its liquid phase. Previous studies showed that Starch gelatinization plays a major role in the final texture and the starch granule size affect the final structure and volume of the end product. Although more thorough studies are required[25]. Moreover, these chemical reactions are represented by

$$A \xrightarrow{k_1} R \xrightarrow{k_2} S$$

- A *ungelatinized starch*
- R *swollen granules*
- S *solubilized starch*
- k_1 *and* k_2 *rate of reactions*

Complete starch gelatinization, which occurs in the presence of heat, is an indication of a completely baked bread. In addition, gelatinization should be completed before the bread starts acquiring its texture and color. Zanoni et al. [26] proposed the following equation for starch gelatinization:

$$1 - r = e^{-k_a t} \tag{18}$$

- α: $the\ degree\ of\ gelatinization$ between 0 and 1;
- k_a: $reaction\ rate\ constant$

- *t: the time*

The rate of reaction k_a depends on temperature in accordance with the Arrhenius equation given by

$$k_a = k_0 e^{-E_a/RT} \tag{19}$$

- $k_0 = 2.8 \times 10^{18} s^{-1}$
- $E_a = 138 KJ / mol$

2. Evaporation and condensation :

Water activity through evaporation and condensation is one of the most important phenomenon occurring in bread baking. It is considered to be a critical issue affecting the overall enhancement in heat transfer through change of phase. The progressive evaporation and condensation of water inside the pores and the diffusion from one pores to another accelerates the baking of the bread. The water migrates to the core of the bread where lower temperature thus more condensation occurs. On the outer side, where the temperature exceeds the boiling temperature no condensation occurs and water vapor is liberated to the oven. Moreover, the moisture content is the chief factor determining the quality of bread. An excess of water content could end up with incomplete baked bread that lacks a good texture and color. On the other side, any deficit in moisture causes early formation of crust and resulting in an unpalatable product.

Evaporation/condensation is governed by the lee model, which is built-in **ANSYS FLUENT®**[27], and is given by

$$\frac{\partial(\alpha_l \rho_l)}{\partial t} + \nabla \cdot (\alpha_l \rho_l \mathbf{u}_m) = -\nabla \cdot (\alpha_l \rho_l \mathbf{u}_{dr,l}) + \dot{m}_{vl} - \dot{m}_{lv} \qquad (20)$$

- $\overrightarrow{V_l}$ liquid phase velocity
- $\dot{m}_{lv}, \dot{m}_{vl}$ *rate of evaporation , condensation*

The above equation is the same as Eq. (13) except that the source term is explicitly written.

3. Release of Co2:

Carbon dioxide is produced by the yeast in the dough. The yeast which is mainly used in bread baking transforms sugar into CO_2 and moisture. Generation of CO_2 occurs between 293°K and 333°K, while peaking at 313°K [21]. This chemical reaction leads to the formation of pores, which represents the basis of volume expansion during baking. The rate of formation of Carbon Dioxide is computed as:

$$I_c = \rho_c R \qquad (21)$$

- ρ_c density of CO_2
- I_c CO_2 production

$$R = R_0 e^{\left(-\frac{T - T_m}{\Delta T}\right)^2} \qquad (22)$$

- R: the rate of formation of CO_2

- T_m: maximum production temperature equal to 313K
- ΔT: equal to 10 K

4. Formation of pores:

During the fermentation of bread yeast secrets CO_2, which is stored locally in small pores causing small volume expansion of the dough before baking starts. While baking, the temperature rises inside the dough. Carbon dioxide expands with the increase in temperature and causing the pressure to increase inside the dough. The dough is considered to be a viscoelastic material[16]. The increase in pressure increases the volume of the pores. In addition, evaporation of water during baking leads to more expansion of pores.

Eventually these pores are connected to each other (Figure 10). This porosity, has a significant effect on the bread baking process. It enlarges the volume of the bread and changes its thermal diffusivity and density [28].

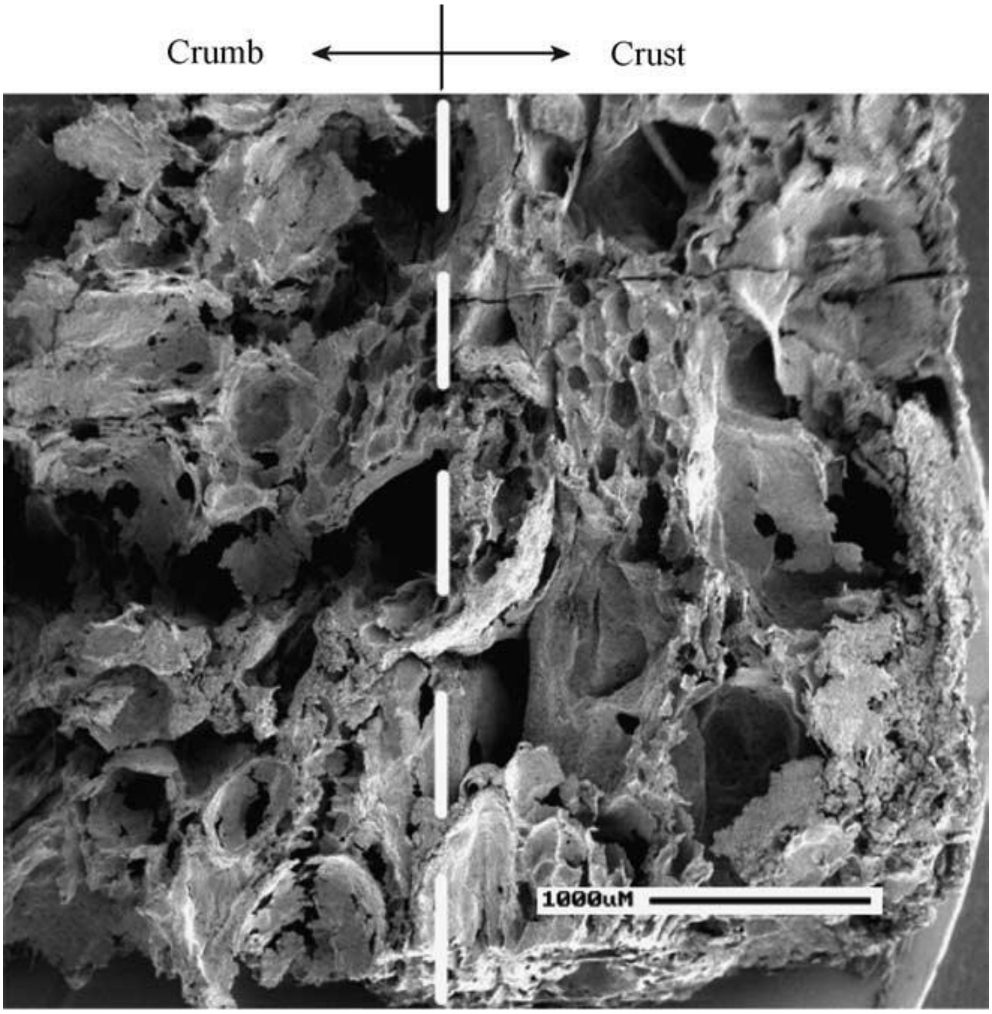

Figure 10: Figure showing the porosity of bread structure **[16]**

5. Volume expansion:

The physiochemical changes (evaporation/condensation, carbon dioxide expansion etc.) occurring inside the bread create internal stresses that lead to volume expansion and bread deformation. The deformation is permanent implying that the dough is a viscoelastic material [16]. This is known by the swelling of the bread during baking. In general, studies aim at maximizing this deformation while minimizing weight loss by evaporation.

Several correlations can be found in the literature modeling the expansion of bread during baking. A widely used correlation is the one suggested by Nicolas et al [29] that models the bread as a hemisphere with its radius $R(t)$ varying with time according to the relation shown in Eq. (23).

$$R(t)=\sqrt{\frac{V_0\beta(t)}{\pi}} \quad (23)$$

Where:

(24)

The variations in the bread radius, described by Equation (23), are plotted in Figure 9.

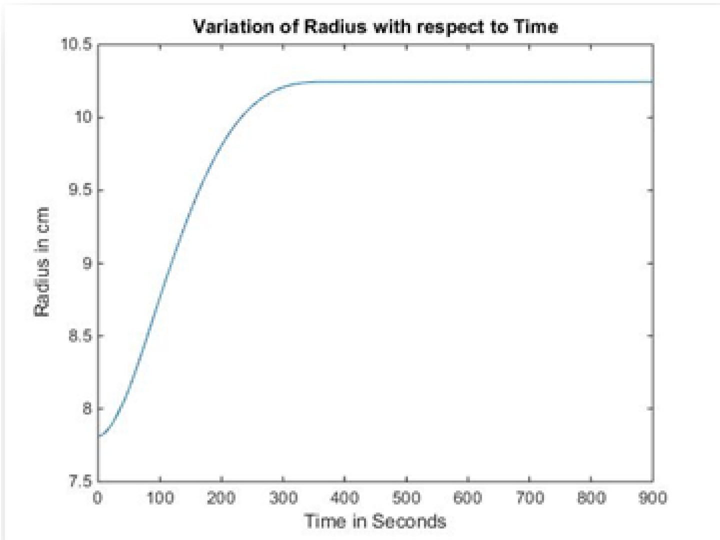

Figure 11: Plot of the variation of radius with time

The specific heat of the bread is calculated as [29]

$$\rho C_p = \rho_s C_p + \rho_l C_{p_l} + \rho_v C_{p,v} \quad (25)$$

6. Formation of crumb and crust layers:

While baking the bread and due to evaporation of water, the outer surface of the dough progressively loses its water content and acquire a brown color. The temperature of this region gradually increases approaching $100°C$ [9] and this layer is called the crust. Inside the bread the moisture re-condenses and defuses deeper into the bread where we have lower temperature. The region is called crumb where the moisture is preserved.

CHAPTER III

RESULTS

The bread is integrated inside the oven during this simulation.

Figure 12: Oven Configuration

The initial temperature of the bread was at 300 K while the oven is preheated to 463 K.

The temperature of flue gases was 1073 K initially. [Figure: 12]

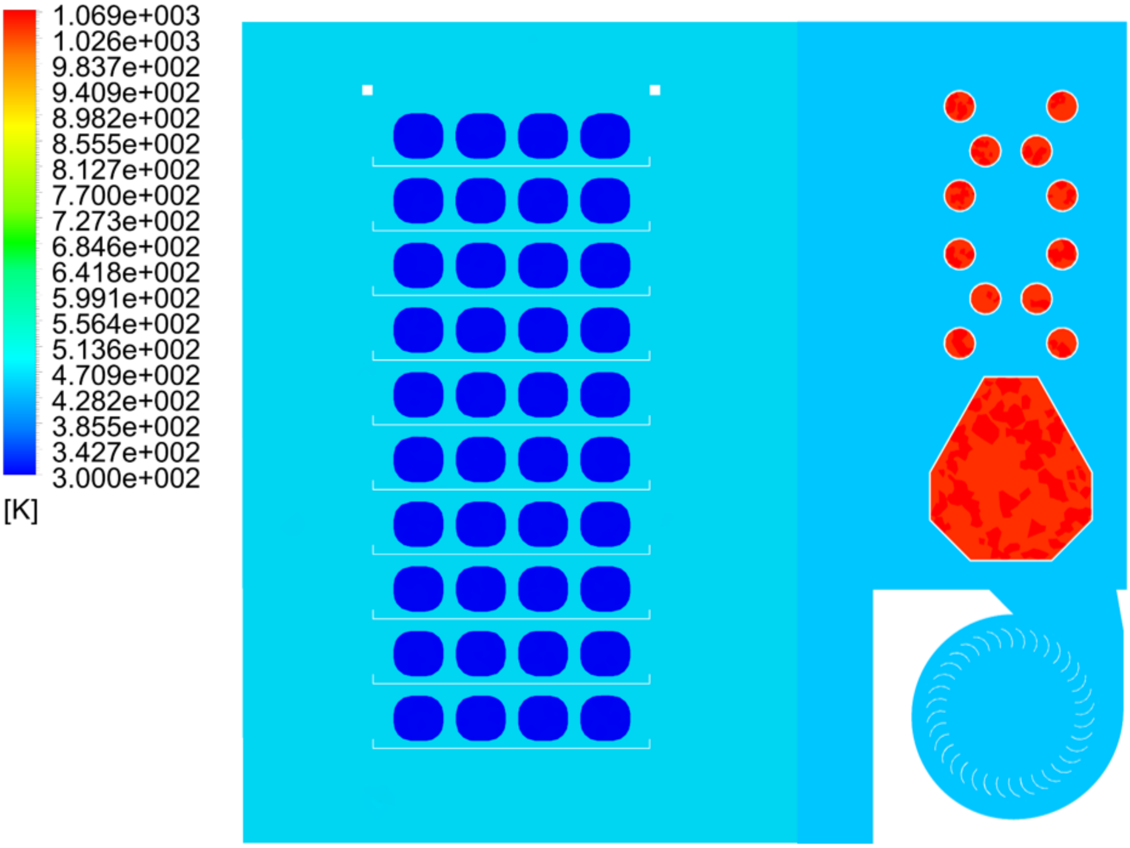

Figure 13: Temperature Contours at Time sec

Figure 14: Water content

The progressive change in temperature is recorded every 30 seconds the contours are shown below. (Figure: 14-20)

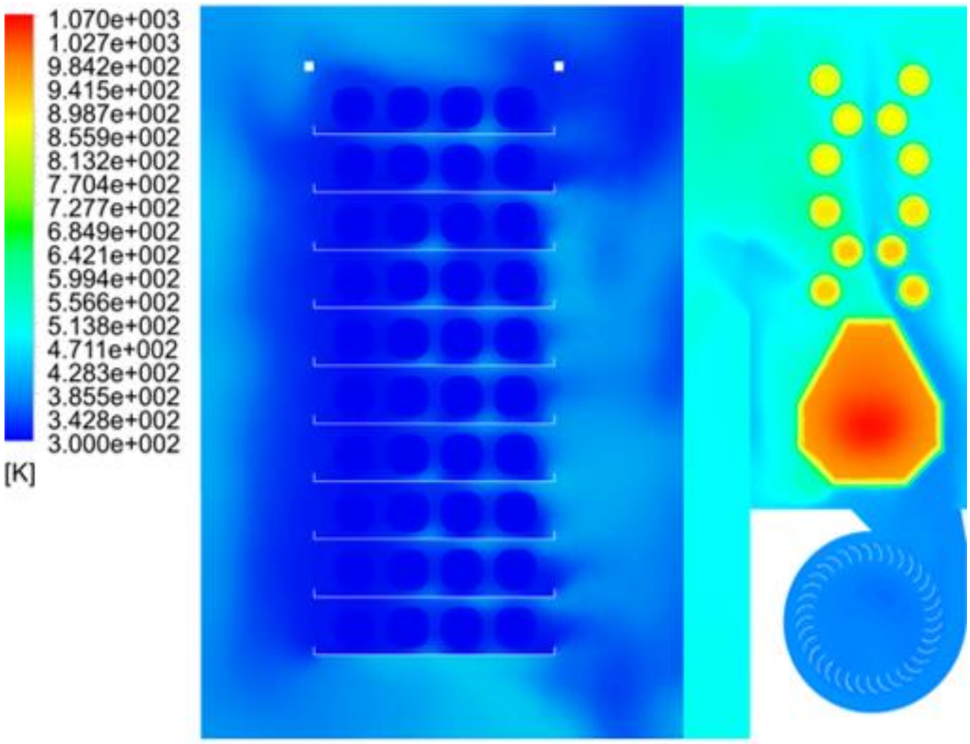

Figure 15: Temperature Contours at 30 seconds

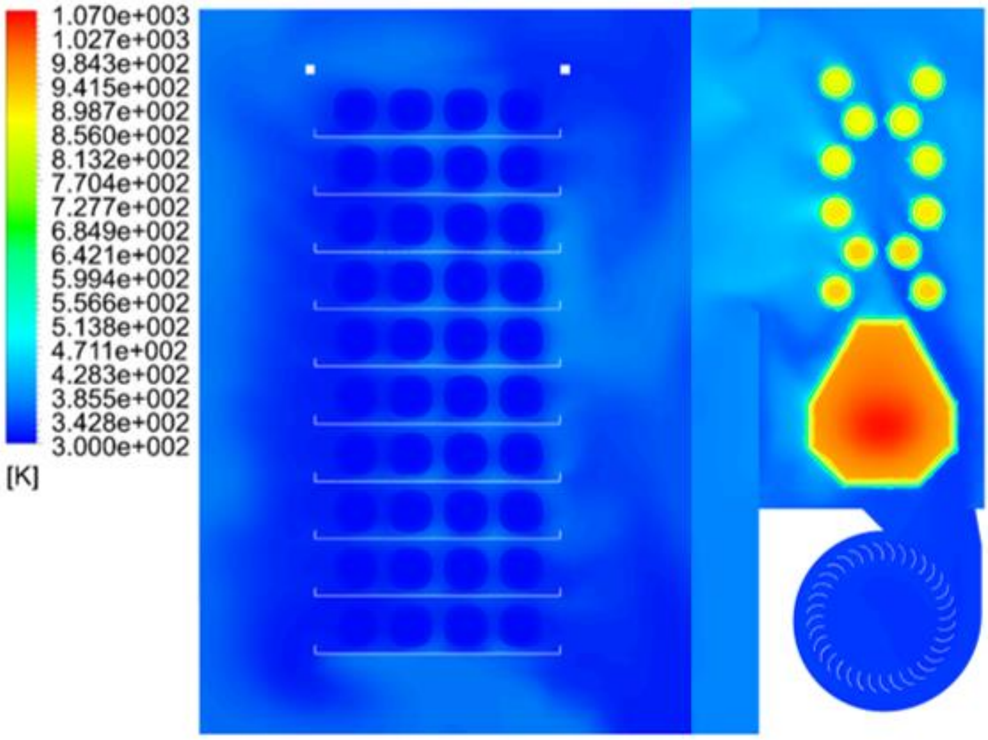

Figure 16: Temperature Contours at 60 seconds

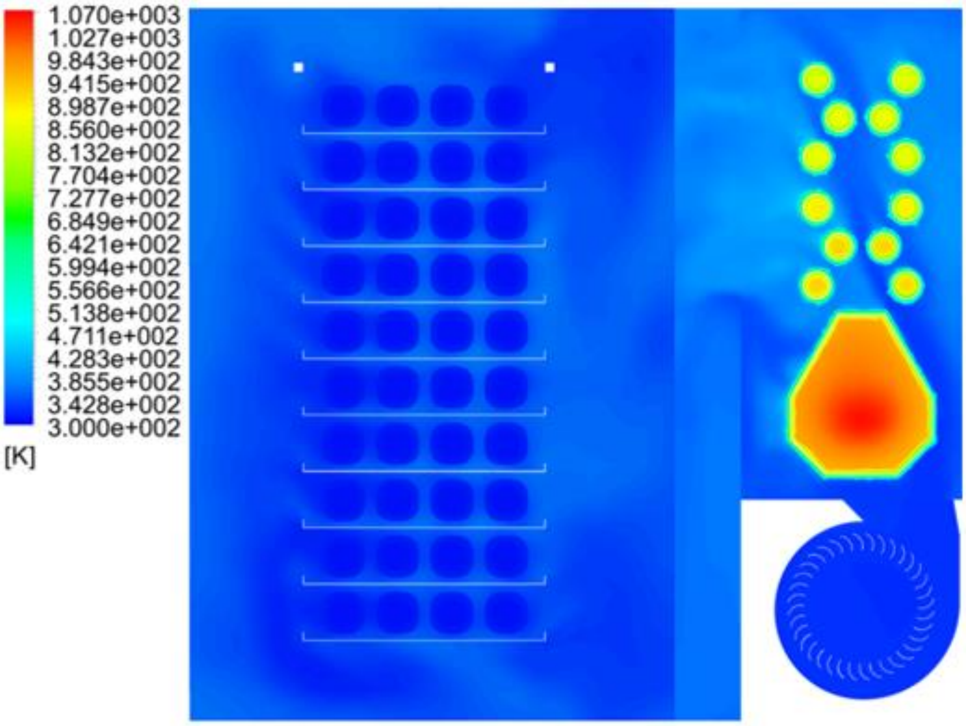

Figure 17: Temperature Contours at 90 seconds.

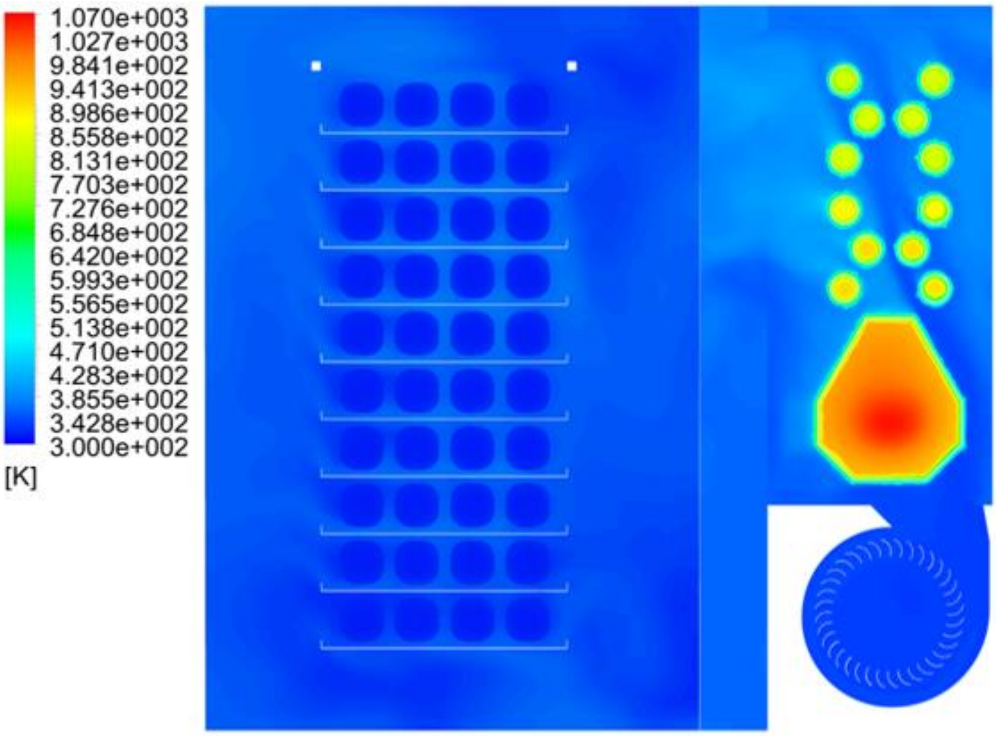

Figure 18: Temperature contours at 120 seconds

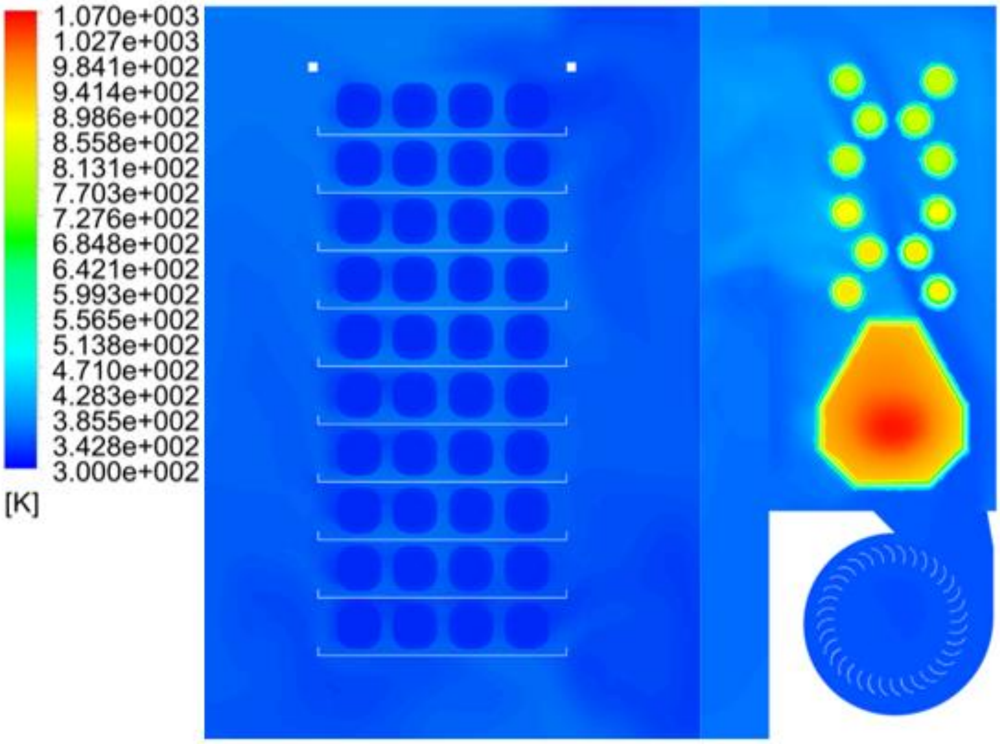

Figure 19: Temperature Contours at 150 seconds

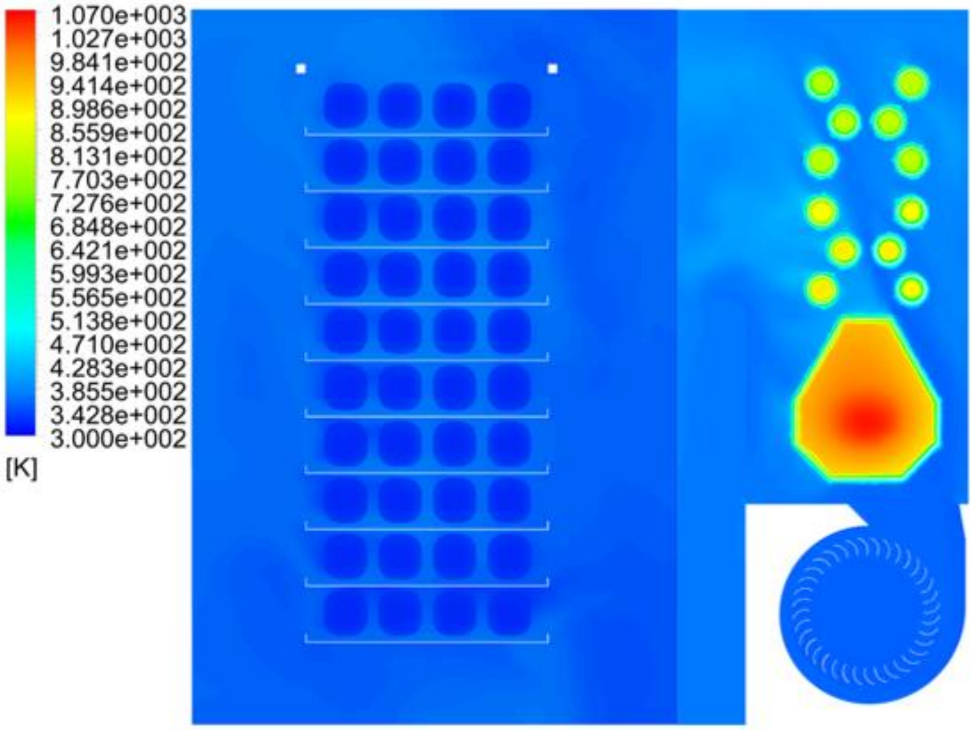

Figure 20: Temperature contours at 180 seconds.

The temperature contours shows a sensible drop of temperature inside the oven upon introducing the bread. On the other side, the bread temperature increases gradually while the heat is transferred from the heat exchanger to the chamber driven by the blower. The temperature contours reveals an equilibrium between the heat fluxes distributed to the bread loafs. However, simulation are still running in order to predict the full baking process.

The initial moisture content inside the bread is taken from the literature 0.54 Kg water/kg dry solid [21] . We accounted for the water liquid phase inside the bread. For the first model the initial content is shown below. (Figure: 13)

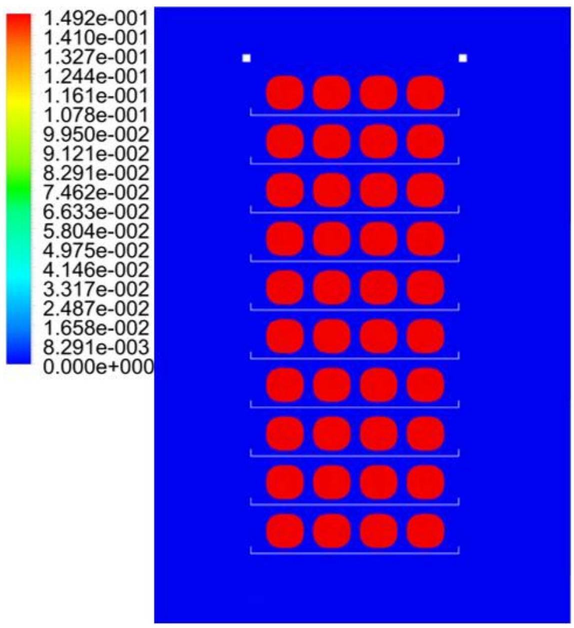

Figure 21: Volume fraction water inside the bread initially

The volume fractions of water and water vapor are recorded every 30 seconds. (Figures: 22- 33). The moisture content inside the bread decreases gradually as baking progresses. This is due to the evaporation/condensation of water inside the bread. The liquid phase is immobile inside the bread. The change of concentrations of water inside the bread is due to the evaporation/condensation process. When water evaporates the water vapor diffuses in all direction where it re-condenses deeply inside the bread loaf where temperature is still low. On the other side of the bread vapor is liberated to the baking chamber and circulates inside the oven. The concentration of water vapor inside the oven increase drastically affecting the thermophysical properties of the air inside the oven.

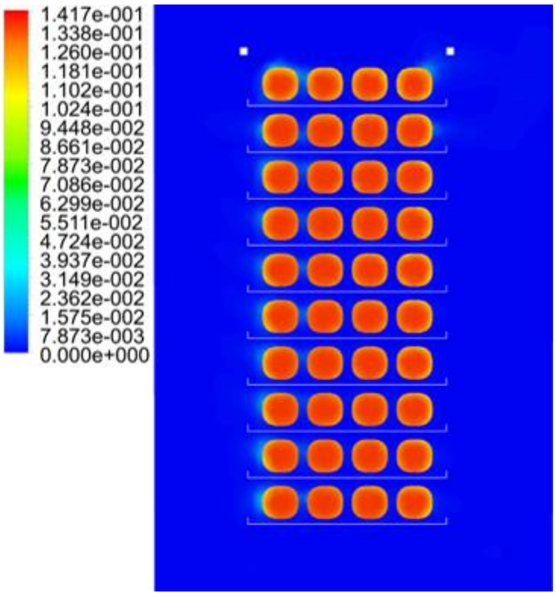

Figure 22: Volume fraction water at 30 seconds

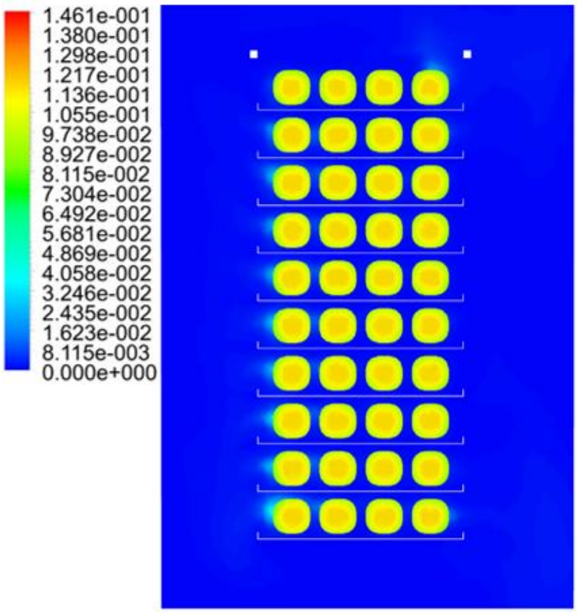

Figure 23: Volume fraction water at 60 seconds

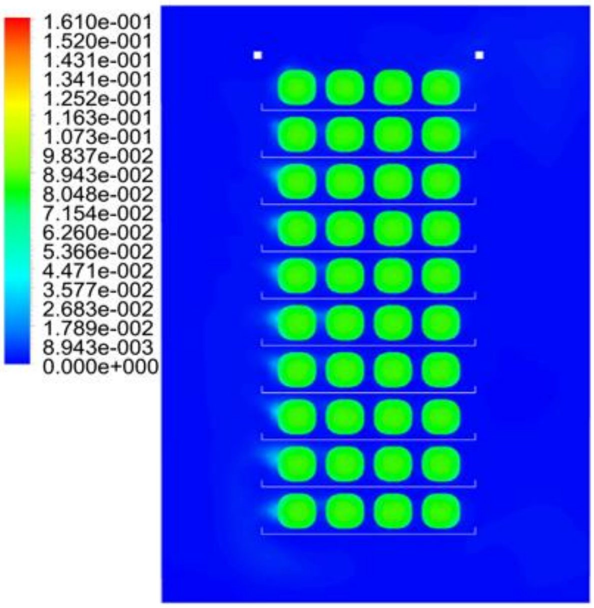

Figure 24: Volume fraction water at 90 seconds

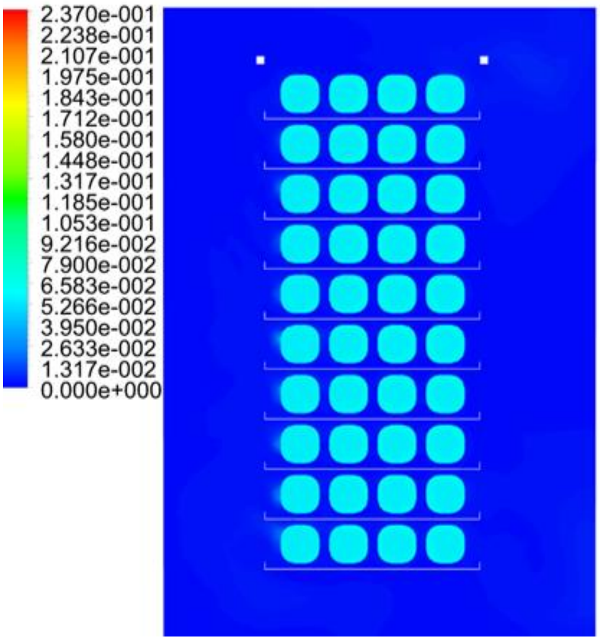

Figure 25: Volume fraction water at 120 seconds

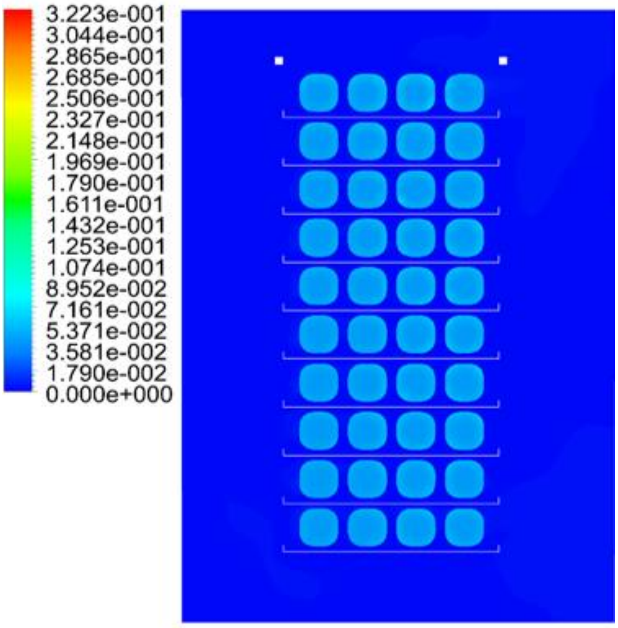

Figure 26: Volume fraction water at 150 seconds

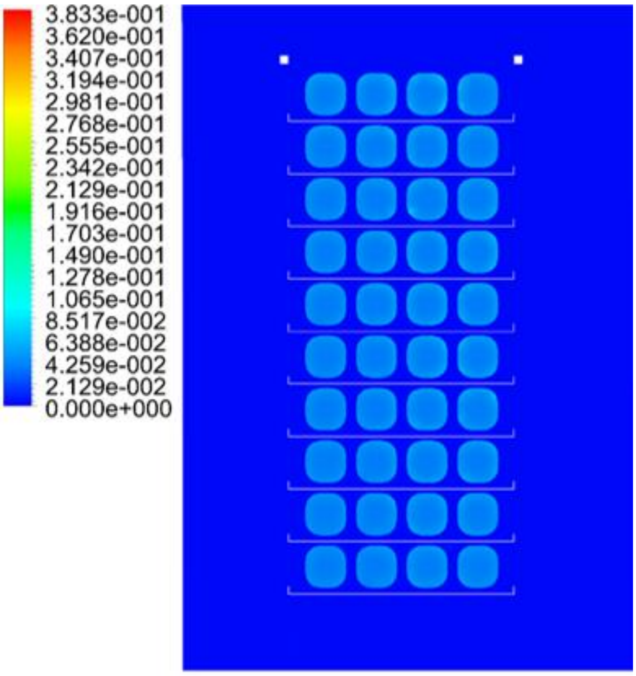

Figure 27: Volume fraction water at 180 seconds

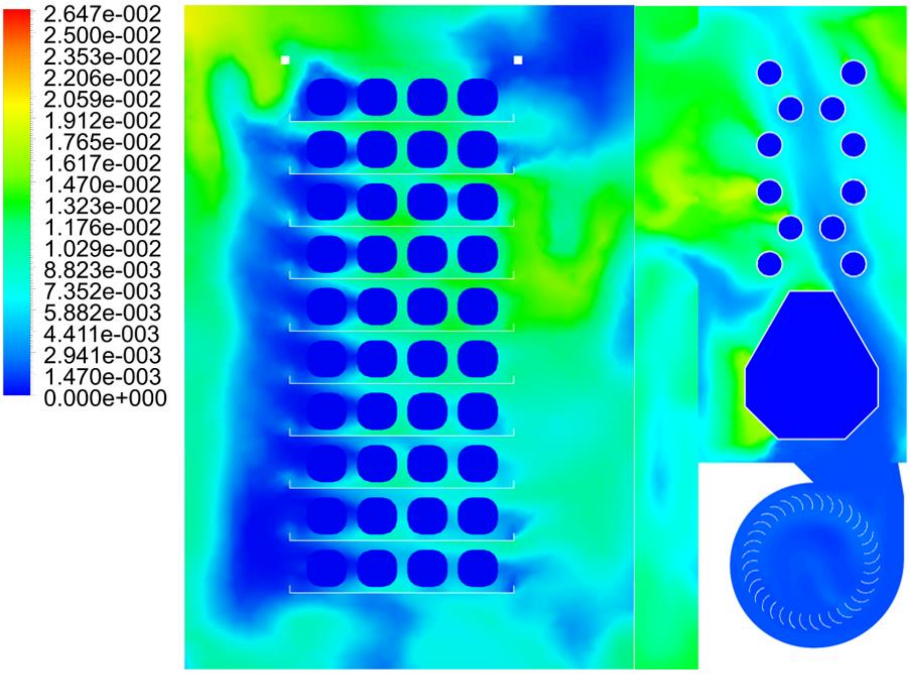

Figure 28: Volume fraction of water vapor at 30 seconds

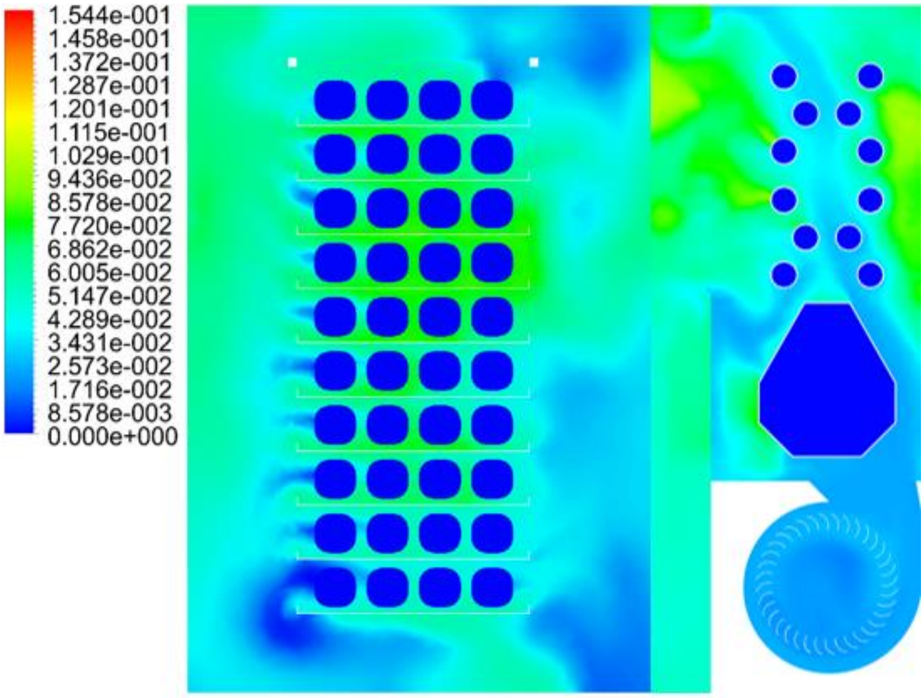

Figure 29: Volume fraction of water vapor at 60 seconds

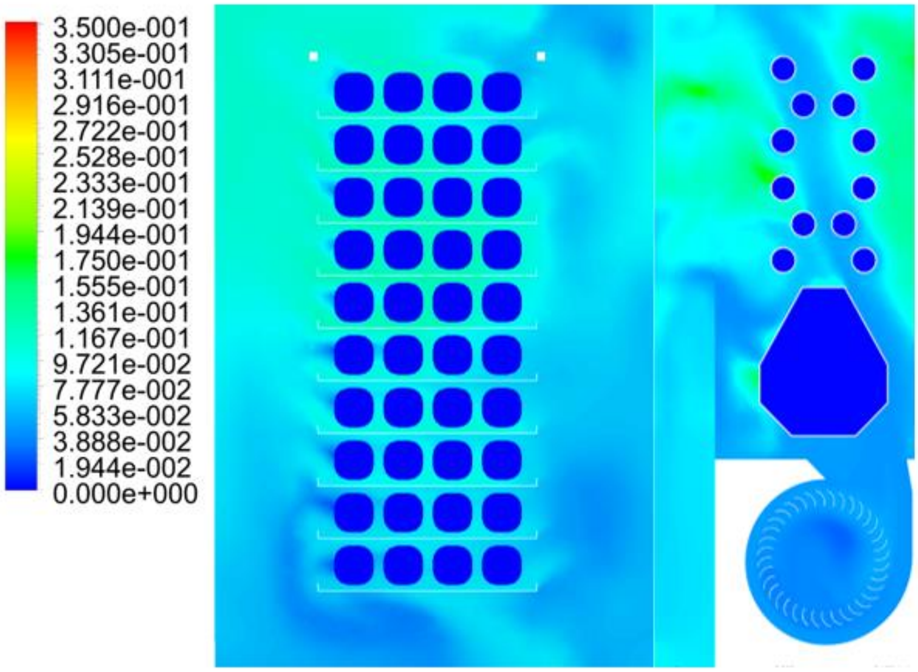

Figure 30: Volume fraction of water vapor at 90 seconds

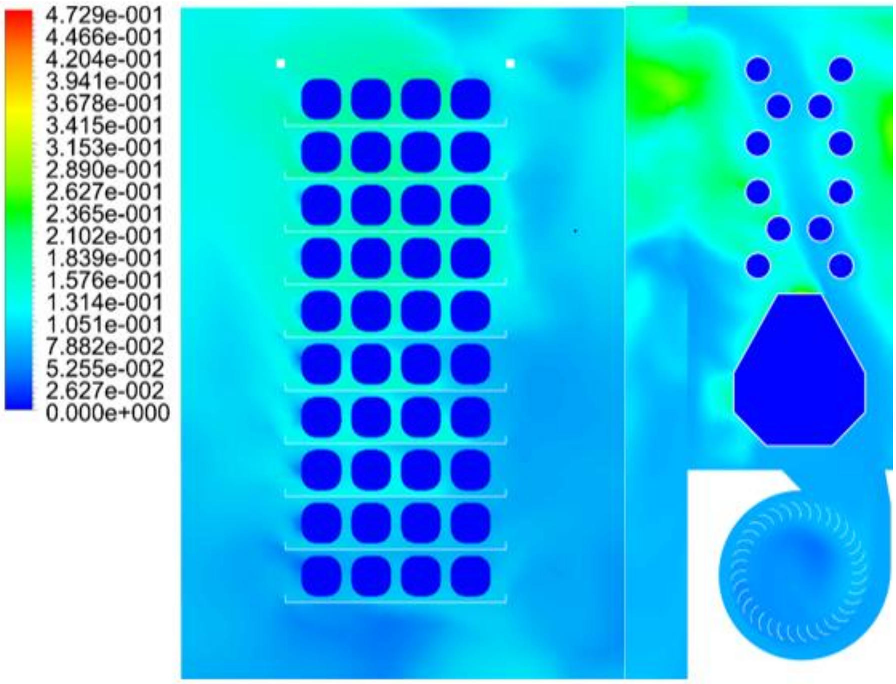

Figure 31: Volume Fraction of water vapor at 120 seconds

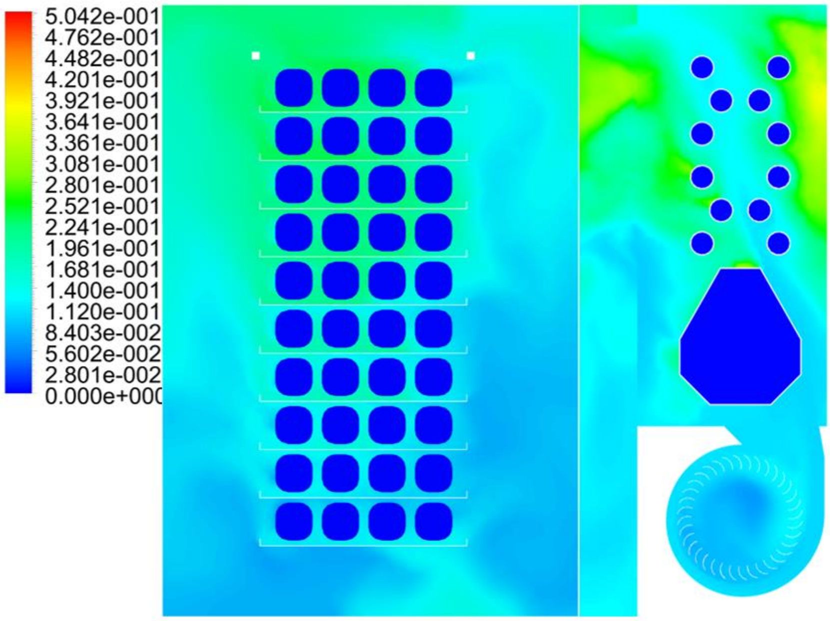

Figure 32: Volume fraction of water vapor at 150 seconds

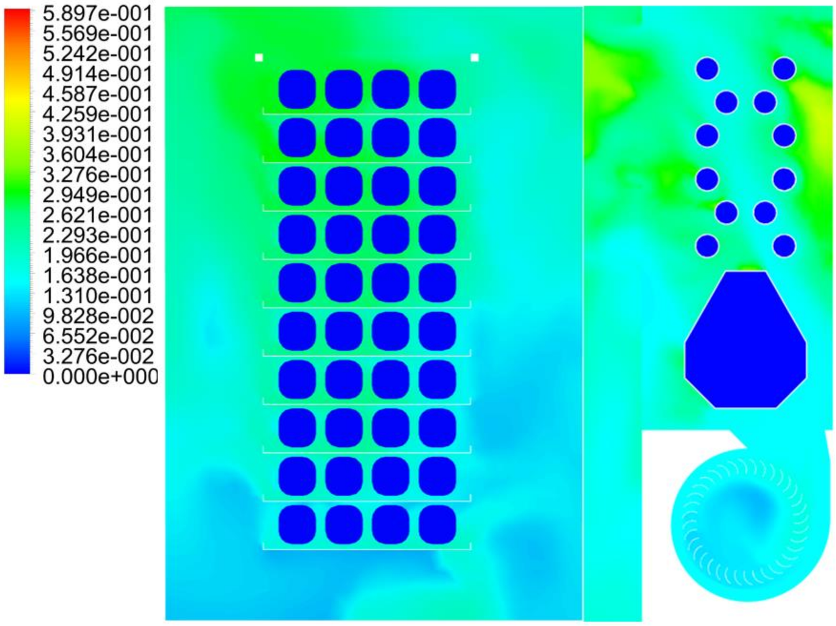

Figure 33: Volume Fraction of water vapor at 180 seconds

Carbon dioxide is produced by the yeast inside the bread. As the temperature of the bread inside the oven increases Carbon dioxide production rate increase to peak at 313 k. before it decays until the yeast is killed at the temperature of 333 K. Moreover, during the first part of bread baking production of carbon dioxide and evaporation of water increases the pressure inside the bread thus volume expansion of bread occurs.

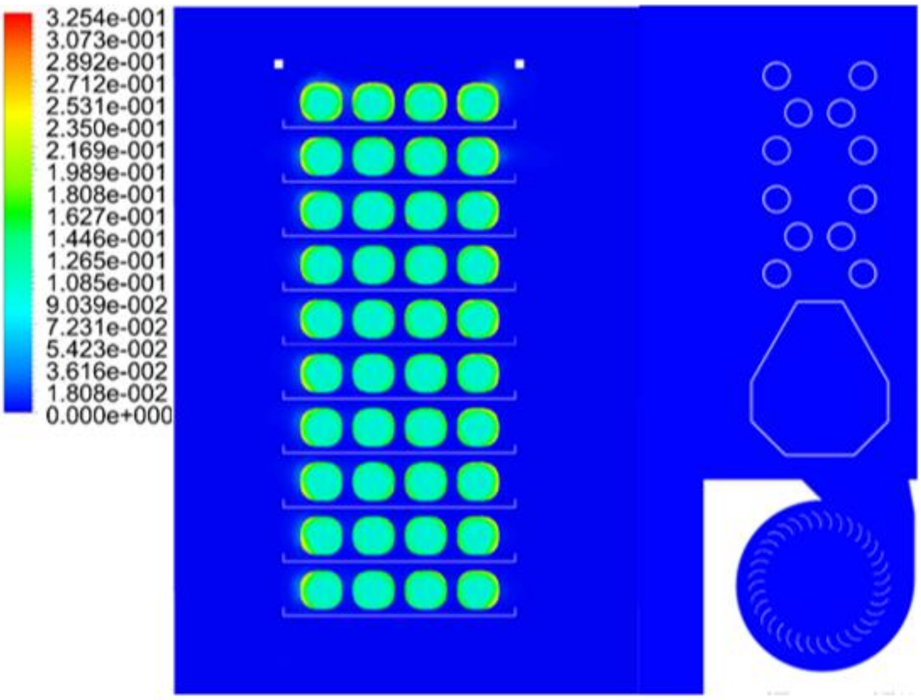

Figure 34: Volume fraction of carbon dioxide at 30 seconds

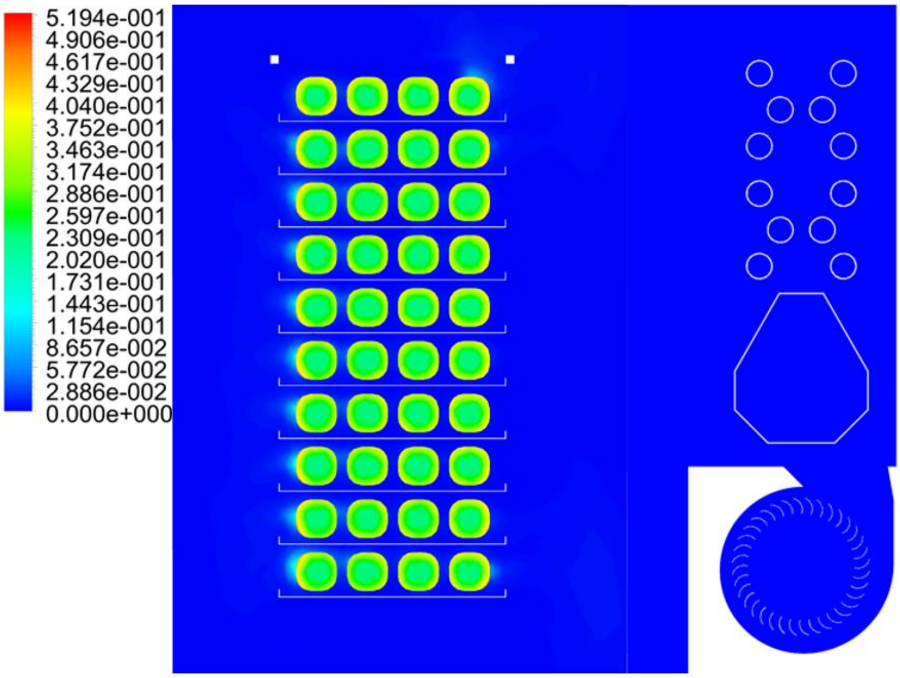

Figure 35: Volume fraction of Carbon Dioxide at 60 seconds

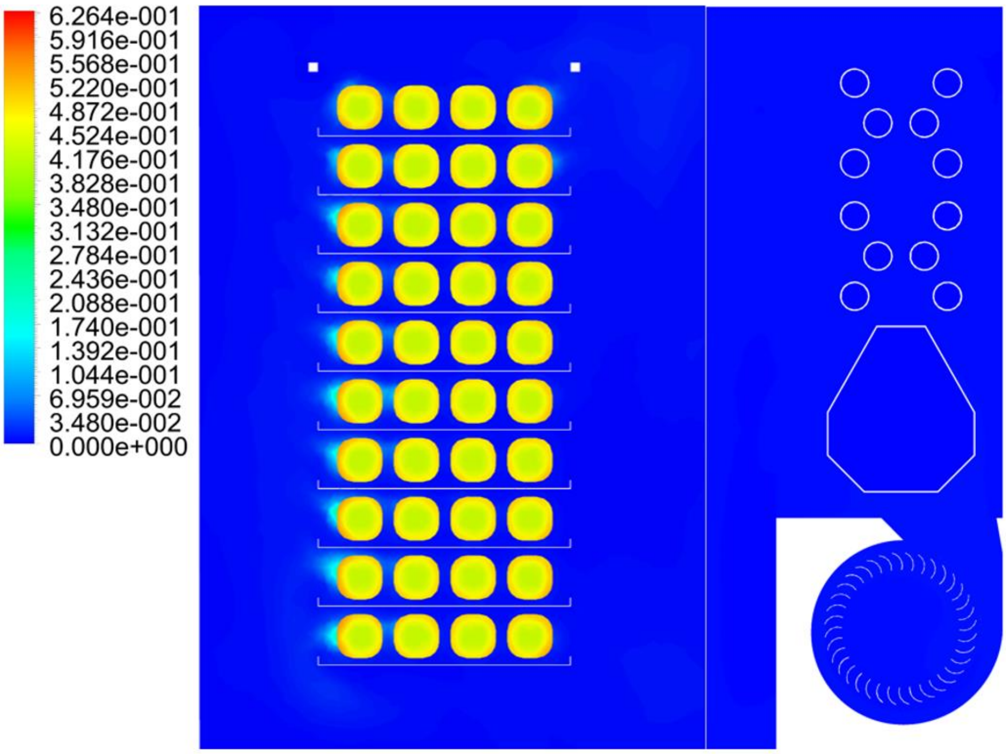

Figure 36: Volume fraction of Carbon Dioxide at 90 seconds

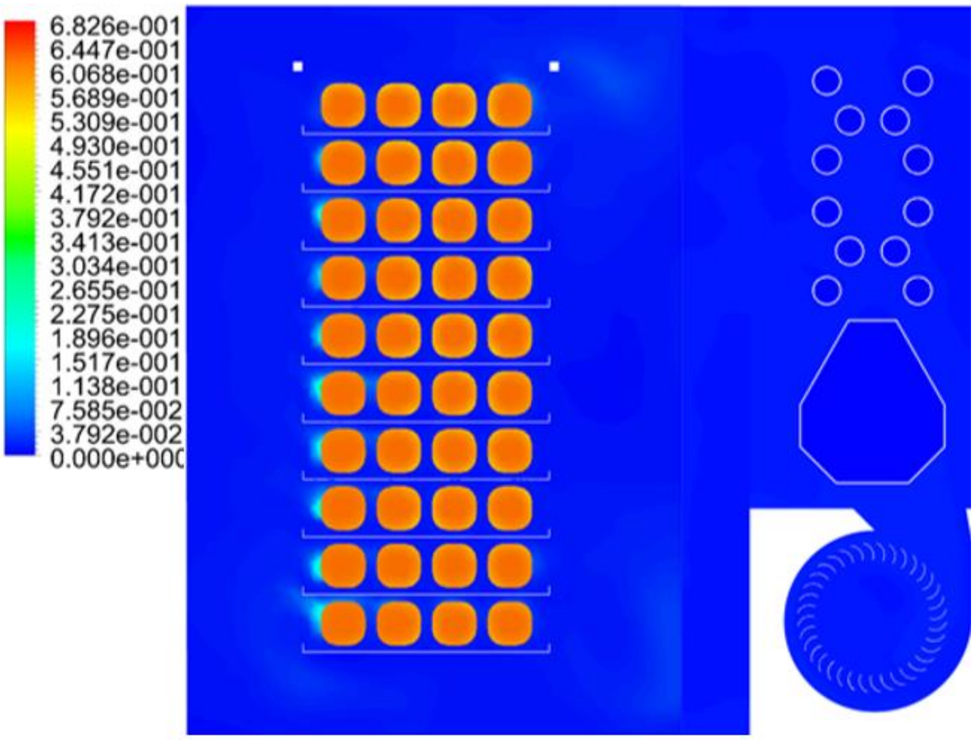

Figure 37: Volume fraction of Carbon Dioxide at 120 seconds

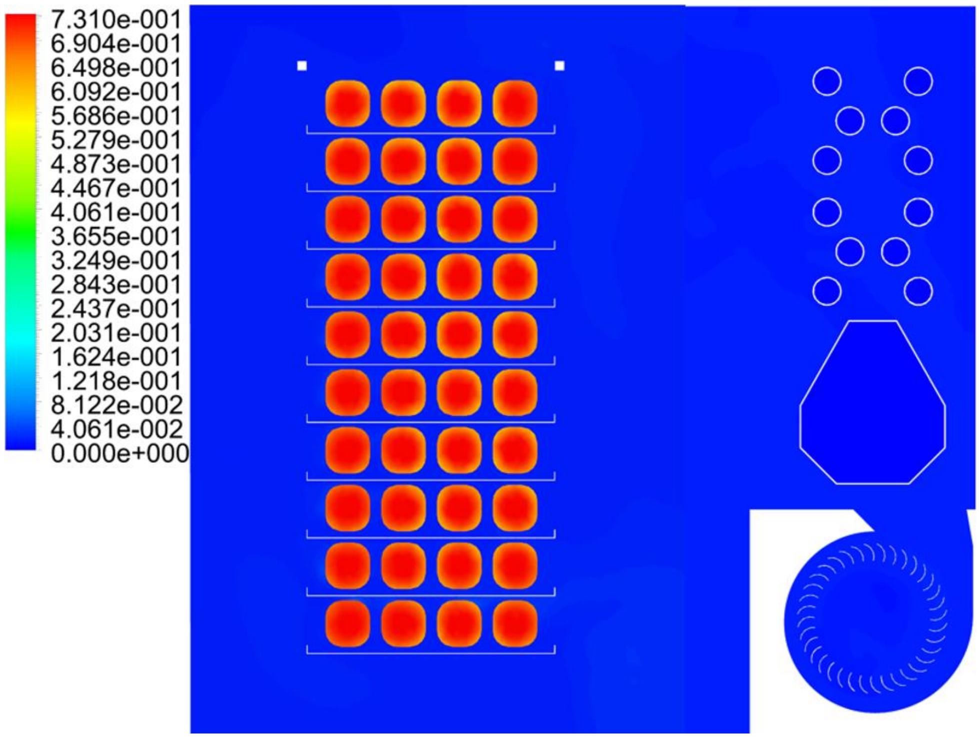

Figure 38: Volume fraction of Carbon Dioxide at 150 seconds

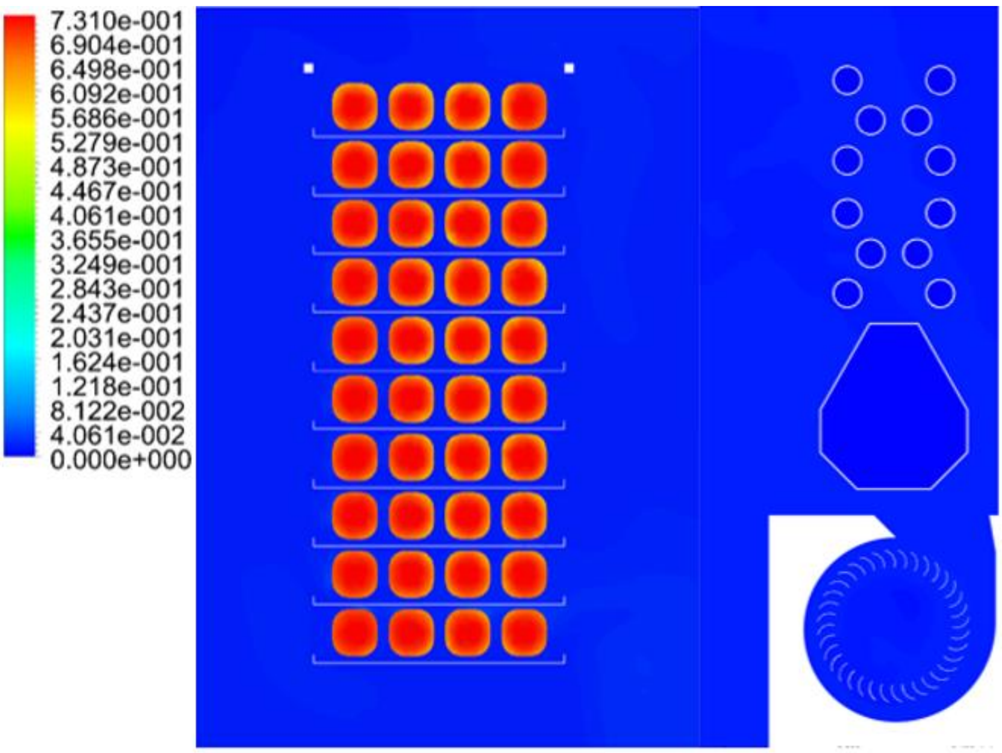

Figure 39: Volume fraction of Carbon Dioxide at 180 seconds

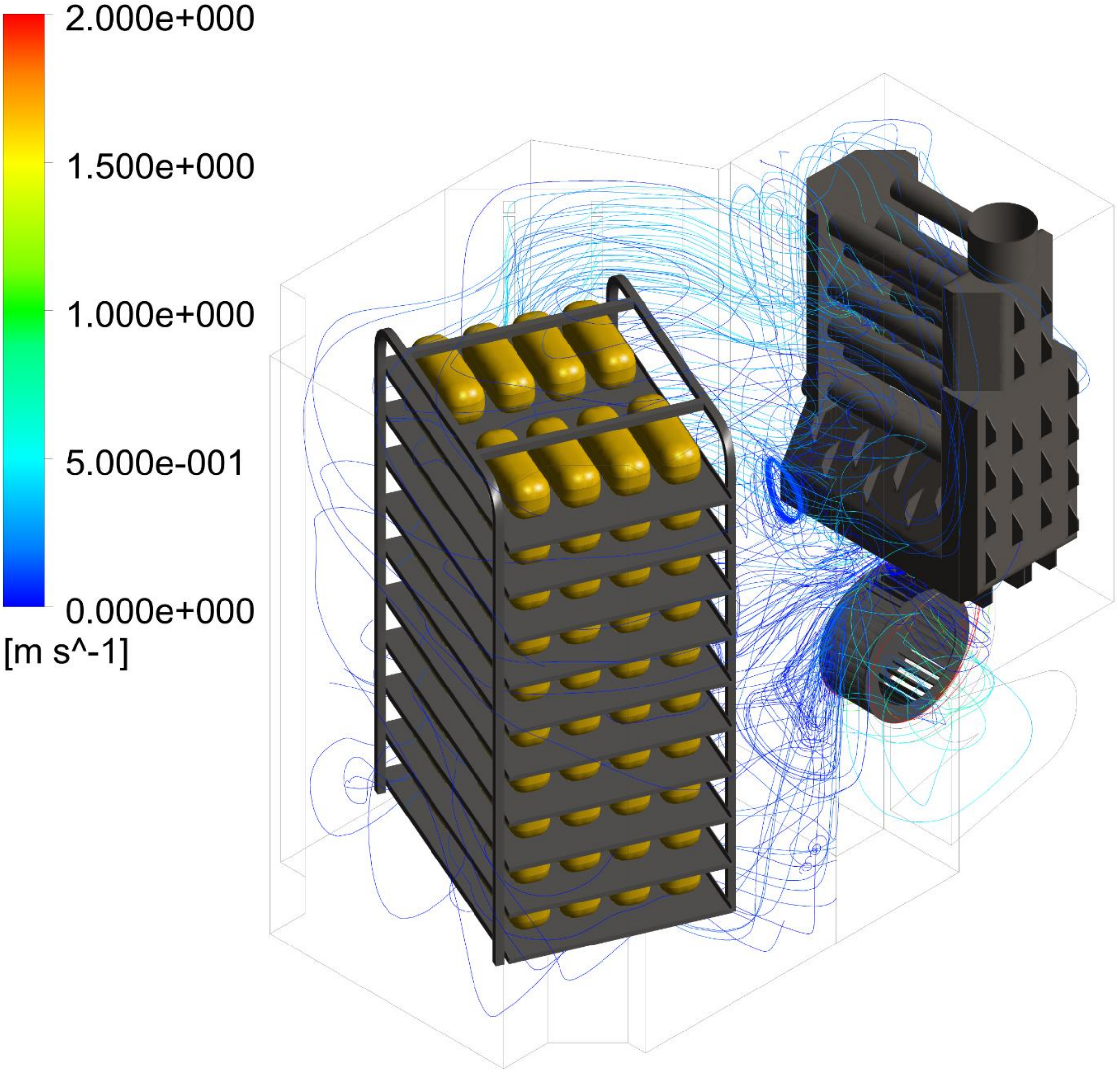

Figure 40: Velocity stream lines

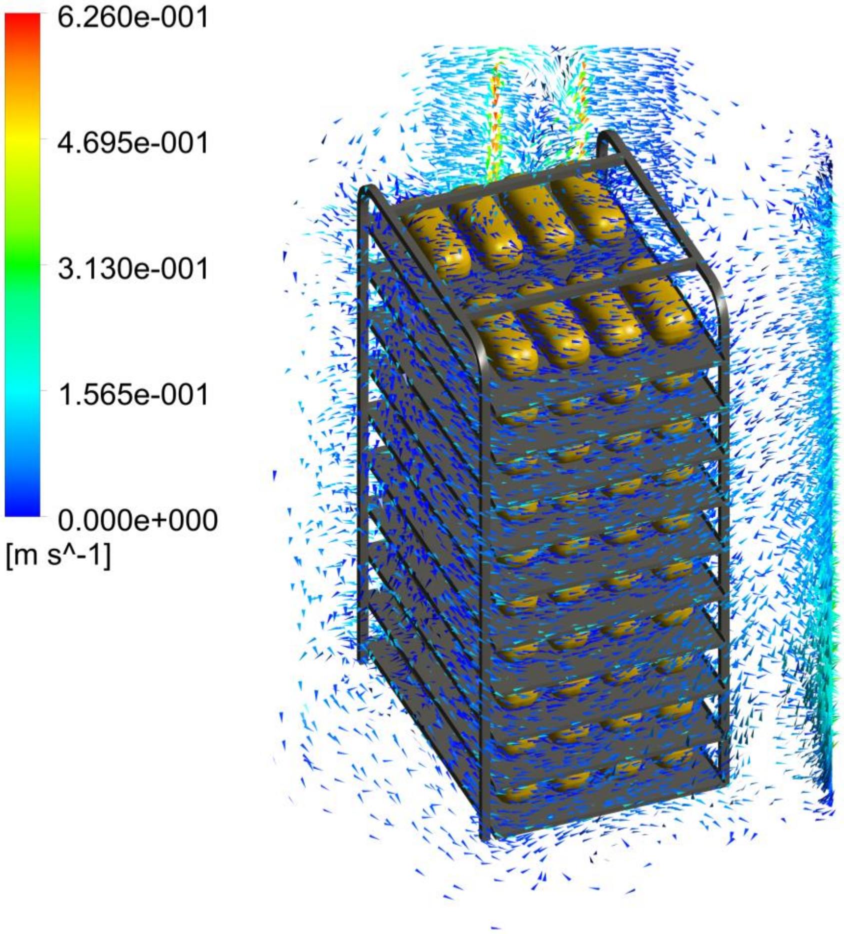

Figure 41: Velocity vectors inside the chamber

The stream lines and the velocity vectors of the flow inside the oven are presented.

The velocity vector and stream lines reveals that a uniform flow field inside the baking chamber. Which can explain the uniform temperature distribution inside the chamber and circulation of water vapor.

The average temperature for both bread and chamber were plotted as function of time.

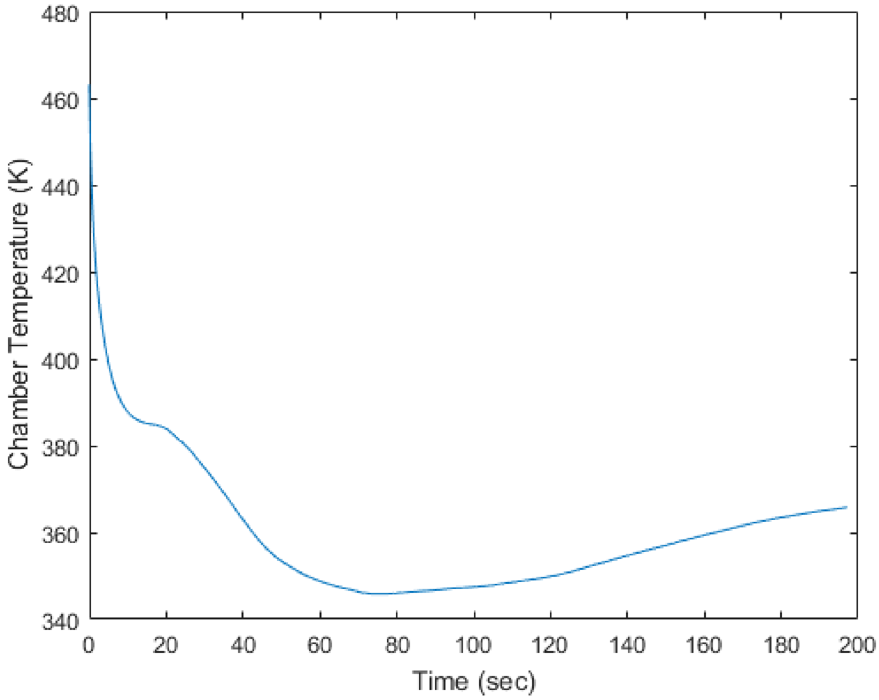

Figure 42: Chamber temperature

The temperature of the chamber initially was 463. When the bread is introduced we sense a very rapid drop in temperature inside the chamber where it reaches it minimum 350 K after 70 seconds before it gradually starts to increase to reach 370 K after 180 seconds and it continues to increase slowly with time.

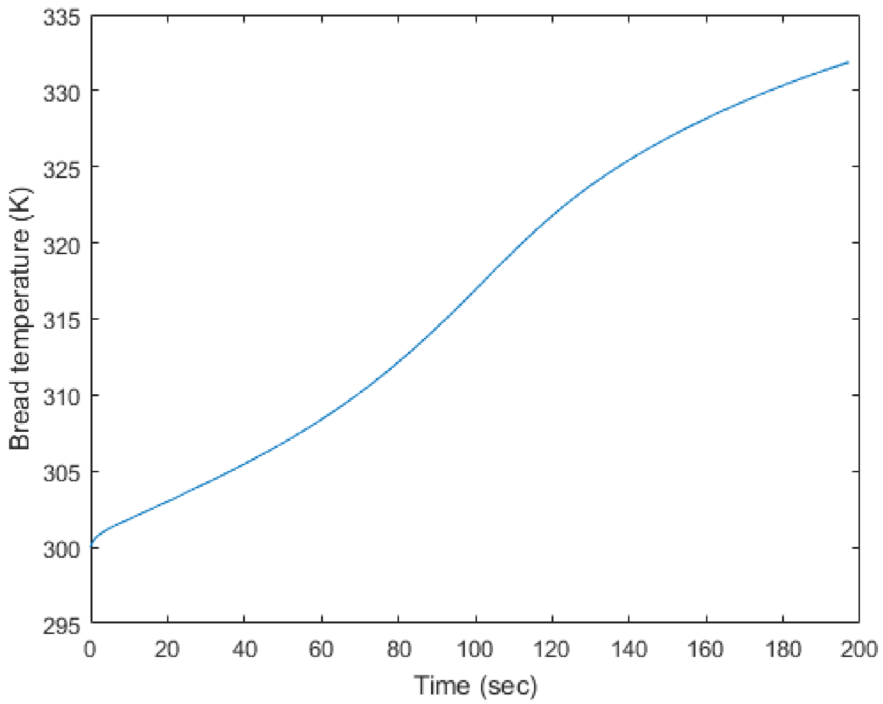

Figure 43: Bread temperature

The temperature of the bread starts to increase at rate of 10 degrees per 1 minute although the rate of increase in temperature is not only dictated by the temperature of the chamber but also a clear relation is revealed between the rate of change of temperature in the chamber and the bread.

Bread baking is expected to take 10 to 15 mins. However more simulation are still required to fully predict the bread baking process.

CHAPTER IV

CLOSING REMARKS

A. Significance of the Project:

The objective of the work is to numerically predict the highly complex baking process in order to improve oven design, optimize fuel combustion, and achieve best bread quality.

B. Challenges and Limitations of the Project:

The main challenges in this project are the high computational cost required to run a detailed simulation for a relatively large mesh while moving in time. Another challenge is the small time step to be used to avoid overlapping of elements and the need to regenerate a new at every time step due to the adoption of a dynamic mesh in the simulation of the blower, and bread expansion. Moreover, the complex physical and chemical changes take place at different length and time scales creating a robustness problem, an issue that should be carefully dealt with to promote convergence.

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